CLIMATE CHANGE AND THE BUILT ENVIRONMENT: AN EVALUATION OF SUSTAINABLE REFURBISHMENT OPTIONS FOR HIGHER EDUCATION BUILDINGS IN THE UK

By

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ABSTRACT

Higher education institutions (HEIs) in England occupy approximately 25 million m^2 of gross space. Many of the buildings in these estates were constructed when thermal standards were far lower than those specified today. Estate managers now need to consider how to manage existing buildings in order to meet new requirements for occupants' comfort, energy efficiency and greenhouse gas emission targets. The choice of whether to refurbish, or demolish and rebuild, requires a critical analysis of a range of environmental, social and economic issues. To this end, the Association of University Directors of Estates (AUDE) developed a toolkit that identifies crucial issues to be taken into account to make this choice clear. However, while this toolkit represents a considerable step forward in the decision-making process, it does not incorporate the projected impact of climate change and its uncertainty.

Thermal modelling analysis of an existing naturally ventilated higher education building, built in 1974, suggests that projected changes in the UK climate will significantly increase building overheating. Therefore, it is essential that the impacts of climate uncertainty now and in the future are considered when refurbishment options are assessed. A framework has been developed, taking climate change impacts into consideration, which ranks different refurbishment options according to the following performance criteria: thermal efficiency, environmental impact and cost effectiveness. Whilst the use of single performance criterion results in different ranking of refurbishment solutions in this case study, the use of high performance glazing is the best overall single refurbishment solution. In general a combination of high performance glazing, wall insulation and the use of external shading together are considered to be the best combined refurbishment solution. External shading is the least effective single refurbishment solution.

DEDICATION

''Little drops of water,

  little grains of sand,

  make the mighty ocean

  and the pleasant land.''

To those who made this possible…

To my father…

His never ending support is invaluable. Without his knowledge and input this work would never have been completed.

His wisdom and patience were a source of inspiration.

His ocean of experience was and always will be the source to quench my thirst.

Indeed his love made everything possible.

To my mother…

Her determination and sacrifice made my life much easier. In fact, she is like a candle that

burns brightly to enlighten our roads.

Without her, I would have never seen the light at the end of the tunnel.

To my brothers, sisters, friends and colleagues…

Your support, consideration, affection and encouragement made everything possible.

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Finally, I would like to use this acknowledgement as an opportunity to express how much I enjoyed the research process not only the positive but also the more painful times, I benefited from the experience of the great people and friends I met from all over the world.
Best wishes to all of them…

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LIST OF ABBREVIATIONS

AR4: The Fourth Assessment Report.

ASHRAE: The American Society of Heating, Refrigerating and Air-conditioning Engineers.

AUDE: The Association of University Directors of Estates.

BCR: Benefit Cost Ratio.

BRE: Building Research Establishment.

CBD: Convention on Biological Diversity.

CDM: Clean Development Mechanism.

CIBSE: The Chartered Institution of Building Services Engineers.

DCF: Discounted Cash Flow.

DSY: Design Summer Year.

DTM: Dynamic Thermal Model.

EAUC: Environmental Association for Universities and Colleges.

EMS: Estate Management Statistics.

HE: Higher Education.

HEFCE: Higher Education Funding Council for England.

HEIs: Higher Education Institutions.

HVAC: Heating, Ventilating and Air-Conditioning.

ICTs: Information and Communication Technologies.

IES: Integrated Environmental Solutions.

IPCC: The Intergovernmental Panel on Climate Change.

JI: Joint Implementation.

LCCP: London Climate Change Partnership.

OER: Operational CO_2 savings to Embodied CO_2 Ratio.

SRES: Special Report on Emission Scenarios.

TRY: Test Reference Year.

UK: United Kingdom.

UKCIP: UK Climate Impacts Programme.

UN: United Nations.

UNCED: United Nations Conference on Environment and Development

UNCHE: United Nations Conference on the Human Environment.

UNCSD: United Nations Commission on Sustainable Development

UNFCCC: United Nations Framework Convention on Climate Change.

WCED: The World Commission on Environment and Development.

CHAPTER ONE

INTRODUCTION

1.1   Background

Since the middle of the last century, the world has witnessed an increased recognition of the importance of sustainable development for the survival of planet and humankind (Halliday, 2008). The extensive demand for natural resources has accelerated the destruction of planetary ecosystems. The enormous increases in global population and consumption threaten people's quality of life and their ability to survive (Langston and Ding, 2001). The increasing depletion of natural resources has resulted in global shortages and higher prices for many materials and commodities. For example, about 11 million people are added each year to China's population of 1.3 billion and its economy is expanding at a rate of about 10 % annually (Chinability, 2010). China produced over 35 % of the world's steel in 2006, an annual rate of 440 million tonnes and output is still rising rapidly (Kibert, 2008). In 2004, due to the increase in Chinese domestic demand, world steel prices rose sharply leading to a 20 % rise in steel costs to US industry (Kibert, 2008). Since that time, through 2006, steel prices have remained at the same high level (MEPS, 2010). Similarly, global fossil fuel demand is anticipated to increase by 45% by 2030 and oil prices will rise to $200 a barrel (IEA, 2009). These levels of growth and their negative environmental and social impacts cannot go unabated if the global economy is to be sustainable.

Sustainable development focuses on improving the quality of life for everyone now and for generations to come without increasing the use of natural resources beyond the capacity of the environment to supply them indefinitely (Langston and Ding, 2001). The high levels of material and energy consumption in the built environment, and the associated pollution and waste, imply that the construction industry has an important role to play in contributing to the overarching vision of sustainability. Different drivers have been pushing the construction industry to make buildings more energy efficient: first the oil crisis of the 1970s (ACE et al., 2008), then the aim for sustainable development (WCED, 1987) and more recently the concerns about the depletion of fossil fuels reserves, peak oil (Bentley, 2002; MacKay, 2009) and climate change (IPCC, 2007).

Climate change as a result of increasing concentrations of human-generated greenhouse gases (i.e. CO_2, methane and other gases) in the atmosphere is a clear symptom and a direct outcome of unsustainable development (Jenkins et al., 2009). Climate change poses a serious threat to every institution in society including the higher education institutions (HEIs) and their host communities. Through their teaching and practices, HEIs can influence not only the campus or neighbourhoods but also the professional, religious, social communities, governments and non-government organisations. HEIs have a special responsibility to facilitate interactions among these communities by providing scientific knowledge, technological innovations and future leaders (Rappaport and Creighton, 2007).

Additionally, HEIs have unique and ample opportunities to provide good examples for their communities to follow, by reducing their own contribution to climate change and taking actions to leverage their vast resources to deliver projects that reflect their sustainable development goals. These actions include, among others, reducing the energy used in heating

and cooling HEIs's buildings which in England comprises approximately 25 million m^2 of gross space (HEFCE, 2004). Consequently, improving the performance of this existing stock through refurbishment can provide an enormous opportunity for creating energy efficient buildings, reducing CO_2 emissions and saving money in the long term.

However, decision making in the higher education (HE) sector, where asset lives of fifty to eighty years are not uncommon, is beset with uncertainty. For example, increasingly unpredictable energy prices are likely to have a significant long-term impact on the economic viability of different building types. For UK HEIs, projected changes in energy prices, forecast in September 2005, were projected to equate to an additional £60 million to £70 million in energy costs for the financial year 2005/2006 (AUDE, 2005). Given recent geo-political tensions in the oil producing countries, growing global demand for fossil fuels and the increasing reliance of the UK on imported energy supplies, energy price uncertainty, and the HEIs sensitivity to it, seems set to continue well into the future. To reduce the risks imposed by such instability, attempts to minimise energy consumption must lie at the heart of management strategies for the HEI estate.

While the fact that the global climate is likely to change over the coming decades is beyond reasonable doubt, the precise nature of that change remains highly uncertain. In the UK, projections suggest there is a range of equally plausible, but very different, climate conditions that could prevail in fifty years time (UKCIP, 2009). Such uncertainties could have a considerable impact on the thermal efficiency, and therefore, on the long-term sustainability of all buildings. For example, changes in peak and average external temperatures could affect the ability of a given building to provide appropriate internal comfort conditions.

Higher temperatures in some cases might require higher levels of insulation to reduce the risk of overheating, reduce the effectiveness of measures applied to existing buildings to improve their thermal performance, or introduce the need for a cooling load with a concomitant increase in energy consumption (Sanders and Phillipson, 2003). Such uncertainty again poses risks for long term environmental and economic performance, particularly as energy price instability is likely to remain high (Gaterell and McEvoy, 2005).

Clearly, energy performance is a key economic and environmental consideration for HEIs. However, the provision of effective and sustainable refurbishment strategies requires the systematic evaluation of different potential impacts. Any toolkit or framework developed to undertake such evaluation should highlight the key issues that need to be taken into account when identifying the most sustainable refurbishment options and consider the potential impacts of issues associated with each option to ensure a balanced sustainable refurbishment approach.

In 2008, the Association of University Directors of Estates (AUDE) developed a toolkit that can be used to assist HEIs to decide whether to refurbish or demolish and rebuild the proportion of the HE stock built in the 1960s (AUDE, 2008). The toolkit represents an essential first step towards addressing the key issues that need to be considered when identifying the most sustainable options for managing the HE building stock. However, it does not consider the potential impact of uncertainties regarding future climate conditions. Any changes in prevailing climate conditions will undoubtedly have an impact on the thermal efficiency within these refurbished estates and therefore, the long-term sustainability of the building. As a result, any systematic evaluation of a given refurbishment option

necessarily needs to consider the impact of future climate change to ensure it is sustainable and effective over its whole lifetime.

1.2   Aims and Objectives

The overarching aim of this research is to investigate how climate change will affect the social, economic and environmental aspects of refurbishment strategies applied to post-war HE buildings in the UK. In particular, this research will consider how different levels of uncertainty regarding future climate conditions might affect the sustainability and the effectiveness of different refurbishment options applied to HEIs buildings over their whole life time.

To satisfy this aim the key objectives are to:

- understand the concept of sustainable development, its implications in the built environment and enunciate the essential principles that need to be taken into account to achieve sustainable construction;

- understand the basics of climate change and its causes, plausible future climate scenarios in the UK and their associated impacts within the built environment;

- review the current state-of-the art with regard to assessing the sustainability of refurbishment strategies adopted within the HEIs and investigate the potential impacts associated with climate change uncertainties;

- develop a case study building which represents a typical post-war HE building and investigate the potential impacts of projected climate change uncertainties on the ability of different refurbishment options to deliver acceptable indoor comfort

conditions without incurring excessive heating and cooling energy use, cost and CO_2 emissions;

- examine the strategic implications of using various performance criteria in analysing data and the attendant consequences for investment in the HEI estate.

1.3   The Importance of the Project

The importance of this research lies in its considerable practical application in helping HEIs manage their estates in a sustainable and effective way under foreseeable climate change impacts. A particular challenge directly linked to this research is developing a detailed understanding and resolution of the issues surrounding the sustainable refurbishment of post-war buildings, many of which are on university campuses, and taking climate change impacts into consideration. Very little research about this has been done to date and therefore this is felt to be a worthy subject for PhD research supported by the Building Research Establishment (BRE) Trust.

It is hoped that this project is a useful contribution to the sustainability of refurbished buildings on HEI estates. In particular, new knowledge has been gained on the challenges associated with sustainable refurbishment of post-war buildings under a changing climate. This knowledge can be exploited by HEIs for the benefit of their clients, and society as a whole.

1.4   Research Themes

This research comprised the following themes:

1.4.1   Literature Review and Case Study Identification

The literature review helped to establish the existing knowledge on the sustainability in the built environment, climate change and current refurbishment practices within the HE sector and the associated strategies and essential factors that need to be considered.

The Muirhead Tower at the University of Birmingham, which was constructed in 1974, was chosen as the case study building. This case study represented a typical post war HE building which was built during the 1970's and was likely to be in need for refurbishment. Three generic HE room types: cellular office, open-plan office and teaching room within the Tower has been chosen for detailed analysis

Key deliverables:

➢ review of sustainable development and its implications in the built environment, climate change and different refurbishment practices and strategies; and

➢ review of the HEI estate identifying building room types to be considered in the case study.

1.4.2   Analysis of Case Study Building

Understanding the relative sustainability of different refurbishment options available for buildings in the HEI estate is based on a systematic evaluation of the current performance of the case study building (Muirhead Tower), the potential options available to improve such

performance and the relative sustainability of each option. The case study building identified above (Muirhead Tower) was analysed using the following themes:

- Building Performance

Work carried out in this theme indentified weaknesses in current performance, or requirements for future performance, and developed a hierarchy of issues which need to be addressed in any refurbishment strategy.

- Technical, Environmental and Financial Appraisals of Refurbishment Options

This theme helped to identify different refurbishment options available to address the hierarchy of issues outlined above. It examined how the following refurbishment options should be integrated into the existing structure:

- improvement of the as-built wall insulation standards to accomplish with both the current Building Regulation 2006 for refurbished buildings and with the anticipated future standards;

- replacing the existing glazing system to comply with both the current Building Regulation 2006 and with the anticipated future standards;

- introduction of external shading device ; and

- a combination of all options.

Each identified option was developed in detail and evaluated using a software based, thermo-dynamic buildings simulation tool called Integrated Environmental Solutions (IES) and taking into account future climate change uncertainties. IES allows comparisons of different refurbishment options in order to optimise building performance and to improve the quality of buildings indoor environment (IES, 2010). An important aspect was to illustrate the response and analyse the performance of different refurbishment options under different climate change scenarios based on thermal comfort performance and the associated changes in heating and cooling energy use and CO_2 emissions.

A key element of this theme was an investigation of the potential impacts of projected climate change uncertainties on the ability of different refurbishment options to deliver acceptable indoor comfort conditions. UK Climate Impacts Programme 2002 (UKCIP02) provides best currently available scientific projections for UK climate over the coming century (Hulme et al., 2002). UKCIP02 data was used by the Chartered Institution of Building Services Engineers (CIBSE) to develop simulation weather files that represent future climate scenarios (Jenkins et al., 2009).

To facilitate such comparisons (based on UKCIP02 and developed CIBSE's future weather files), two climate change scenarios were considered; a low emission scenario and a high emission scenario. These two scenarios were analysed over three different time slices- 2020s [the period from 2011 to 2040], 2050s [the period from 2041 to 2070] and 2080s [the period from 2071 to 2100] (Hulme et al., 2002). Each refurbishment option was examined under these scenarios and compared with the performance of the building in its current state in 2005 [i.e. no refurbishment]. Finally, a framework was designed to rank different suggested

refurbishment options according to different sustainable performance criteria (i.e. thermal efficiency, environmental impact and cost effectiveness).

Key deliverables:

> detailed refurbishment options designed to address identified performance issues;

> assessment of the impact of refurbishment options on building performance, based on thermodynamic simulations;

> analysis of the contribution of individual refurbishment options to addressing building performance issues;

> analysis of the impacts of climate change uncertainty on the performance of individual refurbishment options;

> prioritisation of refurbishment options based on thermal efficiency, environmental impact and cost effectiveness.

1.5   Thesis Scope and Structural Layout

Following this introductory chapter, the thesis is presented according to the following chapter headings (the content is briefly outlined below):

Chapter 2 explores and describes the emergence of the concept of sustainable development, its rapid evolution over the past century and its major characteristics. This chapter also addresses the application of sustainable development in the built environment, the advance understanding of sustainable construction and it enunciates principles to be upheld in order to attain sustainable construction.

Chapter 3 describes the basics of climate change and the probable causes. It summarises recent trends in both global and UK climate. It also describes future climate change scenarios for the UK and how they were constructed. Moreover, this chapter briefly summarises the likely impacts of climate change both globally and in the UK and actions taken to tackle this change with a particular focus on the built environment and the opportunities that exist within the current building stock.

Chapter 4 takes a very close look at HEIs's buildings and reviews the current state-of-the art with regard to assessing the sustainability of refurbishments or redevelopment strategies in HEIs. This chapter also investigates the potential impacts associated with climate change uncertainty in a university setting.

Chapter 5 describes two different human thermal comfort theories in buildings and identifies different refurbishment options that are likely to be used to improve the thermal performance of the HEIs's buildings.

Chapter 6 presents a detailed case study building chosen from the HE sector. The performance of different refurbishment options applied to elements of this building (i.e. cellular office, open-plan office and the teaching room) is examined under different future climate change scenarios using IES thermal modelling programme. The results of the thermal modelling are also presented in this chapter.

Chapter 7 contains a discussion of the results of the modelling which analyses the effects of applying different refurbishment options on internal comfort and energy consumption and associated CO_2 emissions. The environmental impact and cost analysis of each refurbishment option are also discussed.

Chapter 8 presents the conclusions drawn from the case study and recommendations for further work.

Appendices contain the results of the thermal modelling, environmental impact and cost analysis for elements of the case study building (the open plan office and the teaching room).

CHAPTER TWO

SUSTAINABLE DEVELOPMENT AND THE BUILT ENVIRONMENT

2.1   Introduction

Throughout the 1960s and 1970s the world witnessed the increasing awareness of the need for environmental protection and sustainable development for the survival of humankind. The rapid depletion of natural resources threatens people's capacity to survive and achieve sustainable development. The built environment has a key role to play as one of the major sources of profligate material and energy consumption and its development is one of the biggest factors changing the environment of the world. This chapter presents a historical background of sustainable development and its implications in the built environment and highlights the pivotal role that the built environment can play in achieving sustainable development.

2.2   Historical Background

In the post-World War Two period, the developed world witnessed unprecedented economic growth with extensive consumption of natural resources and little attention was paid to the environment (Halliday, 2008). The current positioning of the environment as a central political issue mainly in the developed world began in the 1960s, when scientific evidence about depletion of the environment became noticeable (Langston and Ding, 2001). It is now

widely recognised that environmental quality and the conservation of natural resources are of paramount importance for humankind today and for generations to come (UKSDS, 2005).

This recognition was first discussed in a book called 'Silent Spring' (published in 1962) which is considered as a turning point in the understanding of the interconnections between the environment, economy and social well-being (Carson, 1962; DTI, 2004). In 1972 The United Nations Conference on the Human Environment (UNCHE) was held in Stockholm. This conference was responsible for transforming the environment into a political issue of international importance. Moreover, it considered the need for a common outlook and principles in the protection and improvement of the human environment (DTI, 2004). In the same year as the UNCHE or 'Stockholm Conference', the 'Club of Rome' (30 influential people from 10 countries, scientists, educators, economists, humanists, industrialists and civil servants, met in Rome) published 'The Limits to Growth' (Meadows et al., 1972). This document emphasised that concerns about pollution, environmental degradation and natural resource depletion were crucial to the long-term future of humanity (Hill and Bowen, 1997).

In 1987, the World Commission on Environment and Development (WCED) chaired by the Prime Minister of Norway, Mrs Gro Harlem Brundtland published a report called 'Our Common Future' or 'Brundtland Report' (WCED, 1987; DTI, 2004). The report brought the concept of sustainable development onto the international agenda. In contrast to the limits to growth viewpoint, sustainable development put more emphasis on the social and economic objectives of society, particularly in the developing world, but highlighted that achieving these objectives was connected with the attainment of environmental objectives (Hill and Bowen, 1997).

In 1992, the United Nations Conference on Environment and Development (UNCED) or the 'Earth Summit' was held in Rio de Janeiro to discuss how to achieve sustainable development (Halliday, 2008). The Summit agreed the Rio Declaration on Environment and Development which set out 27 principles for achieving sustainable development. Also 'Agenda 21' was adopted by the Summit; which is an action plan to pursue the principles of sustainable development into the twenty-first century and a recommendation that all countries should produce national sustainable development strategies. The Earth Summit also established the United Nations Commission on Sustainable Development (UNCSD) which meets every year to monitor progress. Two important UN agreements were signed as well, namely: the United Nations Framework Convention on Climate Change (UNFCCC) to tackle climate change and the Convention on Biological Diversity (CBD) to protect biodiversity (Halliday, 2008). In 2002 the World Summit on Sustainable Development in Johannesburg aimed to review progress in the ten years since the Earth Summit and pledged itself to encourage and promote the development of renewable energy sources to accelerate the shift towards sustainable consumption and production (Omer, 2007).

2.3   What are Sustainability and Sustainable Development?

In the Oxford English Dictionary the word 'sustainability' is derived from the verb 'sustain' which means to support, bear, keep, maintain, or endure. Sustainability can be defined as the persistent ability of a society, an eco-system or any such interactive system to function without depleting key resources and without adversely affecting the environment (ICAEN, 2004). The usual model for sustainability is of three separate but connected rings of environment, economy and society [**Figure 2.1**] (Giddings et al., 2002; Hopwood et al., 2005).
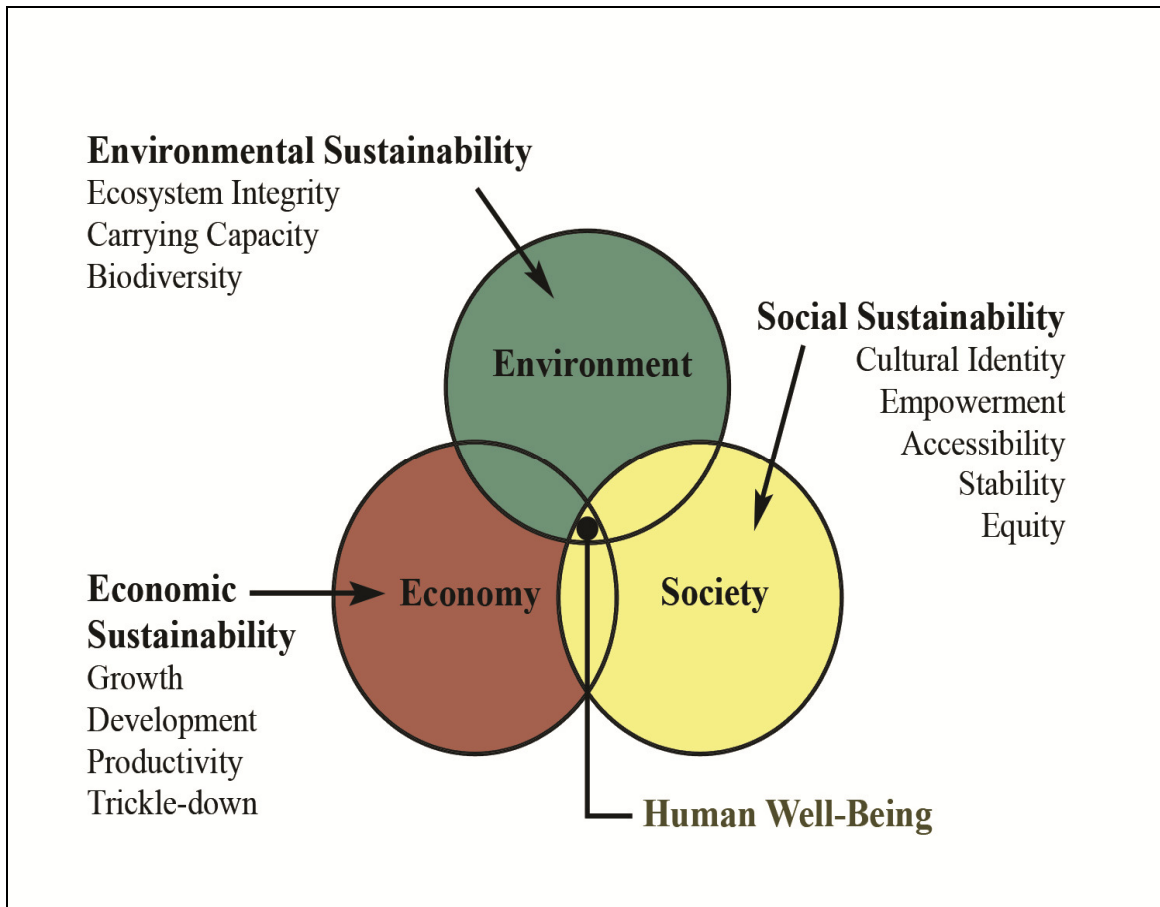
Figure 2.1 Common model of the various dimensions of sustainability
Source: (ICAEN, 2004)

As shown in **Figure 2.1** sustainability has three key pillars to achieve human well being which can be summarised in **Table 2.1** (ICAEN, 2004). Sustainable development is an ambiguous concept, with a meaning that is contested and complex (Carter, 2008). It has been defined, used or interpreted in a variety of ways by different groups (depending on whether it is employed in an academic context or that of planning, business or environmental policy) to suit their own goals (Redclift, 2005). The most popular and frequently quoted definition is the one given in the Brundtland Report published in 1987 (WCED, 1987, p.44):

''*development that meets the needs of the present without comprising the ability of future generations to meet their own needs*''.

Table 2.1 Sustainability Considerations
Source: (ICAEN, 2004)

Category	Implication
Economic Sustainability	• Creation of new markets and opportunities for growth of sales • Cost reduction through efficiency improvements and reduced energy and raw materials input • Creation of additional added value.
Environmental Sustainability	• Reduced waste, effluent generation, emissions to the environment • Reduced impact on human health • Use of renewable raw materials • Elimination of toxic substances.
Social Sustainability	• Worker health and safety • Impacts on local communities, quality of life • Benefits to disadvantaged groups (e.g. the disabled).

The concept of sustainable development emerges as a result of the heightened awareness of the strong connections between the extensive degradation of the environment coupled with socio-economic issues of poverty and inequality and concerns about future humankind health and existence (Hopwood et al., 2005).

Sustainable development seeks to achieve better quality of economic growth, eradicates poverty and ensures human needs are met through a fair share of resources (Baker, 2006). Sustainable development is seen as aiming to bring the three rings of sustainability together in a balanced way and reconciling conflicts (Halsnaes, 2002; Giddings et al., 2002). However, some critics argue that different perspectives might give a greater priority to one or

the other (Carter, 2008). With this vagueness surrounding the meaning and the representation of sustainable development, different views of 'weak' and 'strong' sustainability have emerged (Baker, 2006).

'Weak sustainability' proponents argue that trade-offs can be made between the three rings in the view that focusing on the economic ring through investing in man-made capital can replace or substitute for the depleting of natural resources and the damage caused to the environment (Neumayer, 1999; Dollar and Kraay, 2000; Lomborg, 2001; Pearson, 2006). According to Giddings et al. (2002) weak sustainability views treat the environment and society as a natural and human resource respectively to be utilised and as a sink where problems are dumped whether unemployment, ill health or waste. Solow (1974, p.11) backed these views and went beyond by stating that 'the world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe'.

However, these views have been heavily criticised by 'strong sustainability' proponents (Daly, 1993; Wackernagel and Rees, 1996; Carter, 2008) in that human-made capital can not compensate the loss of natural resources (for instance no number of sawmills will replace a forest, or no improvement in genetic engineering will substitute natural biodiversity) or processes vital to human existence such as the ozone layer or the water cycle (Hopwood et al., 2005). Green parties go further in arguing that non-human species, natural systems and biodiversity have rights and values in themselves (Redclift, 2005; Carter, 2008).

Clearly, whatever view is taken, it is an area of contest and a single definition can not adequately capture all the nuances of a concept which provokes many different responses (Hill and Bowen, 1997; Redclift, 2005).

However, the sustainable development concept in its essence attempts to reassure that there is a possibility to achieve economic growth whilst also protecting the environment without any trade-off and links human equity to the environment (Carter, 2008). It also recognises the dependency of humans on the environment to meet their needs and deliver well-being and not merely as a means to access resources (interdependency of social justice, economic well-being and environmental stewardship) (Houghton, 1999). Humankind lives, economic activities and society are nested within the environment and not separated (Hopwood et al., 2005).

Consequently, any suggested sustainable development principles should apply to all issues (whether they are classified as social, economic, environment, or mix of the three) without giving a priority of one over the other or replace one with the other.

Haughton (1999) has outlined the ideas of sustainable development in five interconnected principles:

- Futurity- intergenerational equity;

- Social justice- intra-generational equity;

- Transfrontier responsibility-geographical equity;

- Procedural equity-people treated openly and fairly; and

- Inter-species equity- importance of biodiversity.

These equity principles clarify the ideas of sustainable development embedded in Brundtland's definition, connect human equity to the environment and provide an intrinsic basis for assessing the different trends of sustainable development (Hopwood et al., 2005).

2.4   UK Sustainable Development Strategy

Following the 'Earth Summit' in 1992, the UK government was the first government to publish its national strategy for sustainable development in 1994 (UKSDS, 2005). A number of sectors of the economy have been identified as significant to sustainable development. Among these sectors were development and construction; energy; manufacturing and services; minerals extraction; transport and waste (Halliday, 2008).

In 1999 the UK government published a document called 'A Better Quality of Life – A Strategy for Sustainable Development in the UK' (DETR, 1999). This document set out the principles of sustainable development in the UK and identified a core set of 147 indicators of sustainable development and provided benchmarks against which future progress could be measured (DETR, 1999). The document was subsequently reviewed, to take account of developments and changes both in the UK and worldwide, culminating in the launch of a new strategy for sustainable development called 'Securing the future: delivering UK sustainable development strategy' in 2005 (UKSDS, 2005).

To achieve sustainable development and deliver a better quality of life, the UK government in its new strategy set out the following guiding principles (UKSDS, 2005):

- **Achieving a sustainable economy-** Building a strong, stable and sustainable economy which provides prosperity and opportunities for all and in which environmental and social costs fall on those who impose them (polluter pays) and efficient resource use is incentivised;

- **Ensuring a strong healthy and just society**- Meeting the diverse needs of all people in existing and future communities, promoting personal well-being, social cohesion and inclusion, and creating equal opportunity for all;

- **Living within environmental limits**- Respecting the limits of the planet's environmental resources and biodiversity to improve our environment and ensure that the natural resources needed for life are unimpaired and remain so for future generations;

- **Promoting good governance**- Actively promoting effective participative systems of governance in all levels of society, engaging people's creativity, energy and diversity;

- **Using sound science responsibly**- Ensuring policy is developed and implemented on the basis of strong scientific evidence, whilst taking into account scientific uncertainty (through the precautionary principle) as well as public attitudes and values.

These principles define the latest UK government approach to achieve sustainable development. They have been used as a framework within which different sectors in the UK shaped their own policies and actions with the aim of achieving a better quality of life and securing a future in which economic prosperity is fairly shared, with less pollution and more efficient use of natural resources.

2.5   Sustainable Construction

Economic growth, rapid increases in population, urbanisation and industrialisation coupled with a profligate exploitation of natural resources have continuously degraded environmental quality (Son et al., 2009). As the demand for construction and development has rapidly increased, these issues outlined above have become increasingly critical for the building professionals around the world (Sev, 2009). The construction industry, which is important to quality of life (in terms of housing, workspace, utilities and transport infrastructure), is a critical sector in delivering sustainable development (Burgan and Sansom, 2006; HM Government, 2008). Both the existing built environment and the processes of adding to it have several environmental, social and economic impacts (Sev, 2009).

Globally, the construction industry is an energy intensive and material profligate sector. Around 40 % of total energy production, 40 % of all raw materials and 25 % of all timber are consumed by this sector and it is responsible for 16 % of total water consumption and 35 % of total CO_2 emissions (Son et al. 2009).

In the UK it provides 8 % of the UK's gross domestic product or £100 billion a year and employs around 3 million people (BERR, 2008). It is responsible for over 25% of all-industry-related pollution incidents. Construction and demolition waste accounts for 19% of

UK waste (Halliday, 2008). The energy used in extracting raw materials, transporting, constructing, operating, maintaining and demolishing buildings is responsible for about 50% of the UK's greenhouse gas emissions (Clarke et al., 2008). As a consequence, the construction industry has a significant impact on the environment and on the ability to maintain a sustainable economy.

Social justice, equality and proportionality are among the key guiding principles in achieving sustainable development in the twenty-first century (Houghton, 1999; Carter, 2008). And since buildings consume more energy than any other single sector in the UK (**Figure 2.2**), it is from this sector that the greatest cuts should be expected (Roaf et al., 2009).

The construction industry, compared with other industries, presents an unusual case in its long life span (Sev, 2009). Structures have an average life of 80-100 years which means that
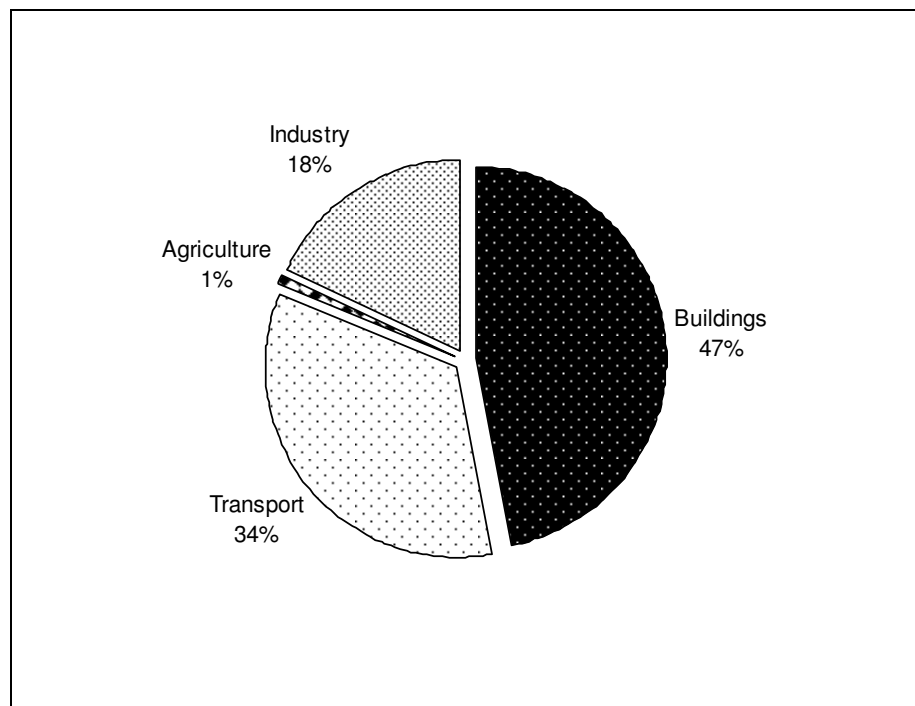
Figure 2.2 Percentage sector shares in total energy consumption the UK
Source: (Sorell, 2003)

the design of an office building for instance will have long term impacts on its economic and environmental performance (Sev, 2009). Therefore, to achieve a high-performance, low environmental-impact structure; it is crucial to incorporate sustainability principles into the entire life cycle of a construction project from planning to the demolition phase (Pearce, 2006; Son et al., 2009).

 'Sustainable construction' or 'sustainable built environment' is a subset of sustainable development which effectively integrates low energy design with materials which have minimum environmental impact (in manufacture, use and disposal) whilst maintaining ecological diversity (Edwards, 1998). Kibert (2008, p.6) defined the goal of sustainable construction as: ''the creation and management of a healthy built environment based on resource efficient and ecological principles''.

While traditional design and construction activities generally focus on cost, performance and quality issues (Latham, 1994; DETR, 1998b), sustainable design and construction add the issues of minimisation of resource consumption, environmental degradation and the creation of a healthy and comfortable built environment (Sev, 2009). Therefore, a sustainable building is the one that is economically viable, environmentally benign and socially acceptable.

2.6   Principles of Sustainable Development in the Built Environment

According to Halliday (2008) and Sev (2009) the basic principles and strategies of sustainable development in the built environment should encompass environmental, economic and social aspects. These principles and strategies are outlined below:

- Maximising the use of renewable, recyclable and natural resources and exploiting them effectively during material selection and sourcing, construction, use or disposal. Buildings have to be affordable, manageable and maintainable in use;

- Minimising the four generic resources used during construction and operation phase (namely: energy , water, land and material), pollution and the negative environmental impacts of the building throughout its life cycle;

- Enhancing biodiversity and improving the natural habitats through appropriate planting and water use;

- Creating a healthy and comfortable environment at home and in workplaces and not jeopardising the health of builders, occupants or any other parties;

- Supporting communities through identifying the real needs, requirements and aspirations of people and engaging them in key decisions; and

- Managing the process to deliver sustainable projects and validate building-system functions and ensure performance over time through indentifying appropriate targets, tools, and benchmarks and managing their delivery.

Some of the sustainable construction principles listed above could be categorised as 'social', 'economic', 'environmental' or a 'combination of all of them'. It is worth noting that optimisation of all the listed principles is not always possible, and that trade-offs and compromises might be necessary depending on the conditions and the particularity of the construction project in question. Moreover, some of the principles can not be considered

immediate priorities, but this does not mean they should be overlooked or neglected (Hill and Bowen, 1997).

2.7   UK Sustainable Construction Principles and Strategies

Sustainable construction principles outlined above have been widely adopted by the UK government in its policy papers, reports and strategies (Hall and Purchase, 2006). Following the publication of 'A Better Quality of Life - A Strategy for Sustainable Development in the UK', 'Building a better quality of life - a strategy for more sustainable construction' was produced in 2000 (DETR, 2000). It highlighted priorities from the UK sustainable development strategy of particular relevance to construction including:

- More investment in people and equipment for a competitive economy;

- Achieving higher growth whilst reducing pollution and use of resources;

- Sharing the benefits of growth more widely and fairly; and

- Improving towns and cities and protecting the quality of the countryside.

Moreover, the document indicated that a sustainable construction approach involves all of the following actions:

- Delivering buildings and structures that provide greater satisfaction, well-being and add value to customers and users;

- Respecting and treating its stakeholders more fairly;

- Enhancing and better protecting the natural environment;

- Minimising its impact on the consumption of energy (especially carbon-based energy) and natural resources; and

- Being more profitable and more competitive.

In 2005 the UK government launched its national planning policy statements for certain features of the spatial (town and country) planning in England to deliver sustainable development through planning systems (DCLG, 2009). These statements cover a wide range of issues such as (housing; biodiversity and geological conservation; waste management; pollution control; flood risk etc.) and ensure that all developments and use of land are implemented in a way to deliver a healthy living environment.

In 2006 a 'Review of Sustainable Construction' document was published in recognition of the significant policy developments since 2000 and aimed to provide an effective basis to guide future government policies where they are relevant to construction (DTI, 2006). In 2008, a strategy for sustainable construction was launched which is a joint government / industry initiative (HM Government, 2008). It identified specific collaborative actions and commitments by both the industry and the government to deliver sustainability in the construction sector.

Clearly, incorporating the above principles, planning policies and strategies in any new building design is likely to result in buildings that have: lower operational and maintenance cost, lower air pollution, healthier and more productive occupants, less material use and longer building life.

However, in the UK, around two thirds of the building stock that will be standing in 2050 has already been built (HM Government, 2008). Ensuring sustainability of this existing stock

will be a critical element in delivering the UK Government's long term sustainable construction strategy.

2.8   Existing Post-War Building Stock

The construction environment in the UK in the immediate post-war period was dominated by a tremendous and urgent need for new buildings especially housing, universities and schools after the trauma of the Blitz when in London alone, for example, up to one in six were made homeless (O'Rourke, 2001). The crippling shortages of resources namely: steel, bricks, timber and labour at that time, encouraged the use of concrete and the search for high speed and cheap construction methods (Bullock, 2002).

By 1955, 'modern architecture' or what is called 'the modern movement' in architecture had been established and became the style of choice in Britain (Bullock, 2002). Many modern curtain walled flats, schools, universities, offices and other public buildings design of that era have been influenced by the values of the modern architecture of 'Le Corbusier' (Banham, 1984).

In his famous book 'Vers une Architecture', translated into English as 'Towards a New Architecture' which was published in 1926, Le Corbusier summarised his modern architectural theories in five points (Le Corbusier, 1999):

- The pilotis lifts the mass off the ground;

- The free plan is achieved through the separation of the load-bearing columns from the walls subdividing the space;

- The free façade, the consequence of the free plan in the vertical plane (replacing traditional walls and windows with curtain walls);

- The long horizontal sliding window;

- The roof garden, restoring the area of ground covered by the house.

According to Roaf et al (2009) of those five points only the roof garden can improve the thermal performance of a building in some temperate climates. Elevating the building off the ground will separate it from the stable temperatures of the ground and expose the bottom face of it to the unstable climate of the air. Creating a deep plan building will make natural ventilation problematic and impose the use of mechanical cooling as only relatively shallow plan buildings can be effectively naturally ventilated (CIBSE, 2004). Using curtain walls or long horizontal sliding windows will result in increased exposure of occupants to the external climate and easily eliminate any applied ventilation or shading strategy (Roaf et al., 2009).

However, Le Corbusier argued that the development of technologies, machines and construction systems based on modern industrialisation will encourage the continuous inspiration and innovation in building design, solve any future building problems and extricate designers from traditional architecture (Banham, 1984).

As a result, the 'traditional architecture' of stone or brick masonry façades was replaced by the 'modern architecture' of frame buildings faced with lightweight concrete panels and large expanses of glass (Parkes, 2001; Bullock, 2002).

The growth of the 'modern building' concept, with both public and residential buildings having lightweight partitions and thin external walls with large areas of glazing, has led to high summer heat gains and high winter heat losses (Roaf et al., 2009).

The advent of heating and air-conditioning systems would make this building design thermally comfortable to its occupants all over the year assuming cheap and limitless energy to fuel was available (Banham, 1984). It also meant that buildings could be constructed at maximum speed and for minimum cost, which suited the post-war building boom era (Roaf et al., 2009).

However, energy costs are likely to rise dramatically as a result of fierce international demand and competition (Kibert, 2008). In the annual publication of the International Energy Agency's World Energy Outlook in 2009, it was predicted that global energy demand will increase by 45% by 2030 and oil prices will rise to $200 a barrel (IEA, 2009).

The increasing uncertainty surrounding the current and future energy prices suggest that modern movement buildings style of Le Corbusier, which shaped most of the post-war UK buildings, will become increasingly unsustainable and unaffordable. Therefore, there is a pressing need to improve the energy efficiency of this stock and draw attention towards more energy efficient design of new buildings, upon which twenty-first century building design will be increasingly inspired, shaped and styled.

2.9   Energy Efficient Buildings and Passive Design

In the UK, buildings account for almost 50% of energy demand and associated CO_2 emissions namely for electricity, heating, cooling, ventilation and lighting (DEFRA, 2008). In its Energy White Papers (DTI, 2003, 2007) and Energy Efficiency Action Plans (DEFRA, 2007a) the UK government outlined its strategy to accelerate the transition towards an energy efficient and low carbon economy. Within this strategy, the UK government recognised the significant contribution and the vital role the built environment can play to deliver a sustainable energy economy. It set out an ambitious target to reduce the built environment's carbon emissions by up to 11.7 million tonnes of carbon per year by 2020 or 8 % of total UK carbon emissions in 2005 (DTI, 2007, Clarke et al., 2008).

Designing a sustainable and energy efficient building to meet carbon reduction targets outlined above is not a straightforward process due to the complexities of many influencing factors. However, according to Thomas (2006) the starting point should consider passive design.

Passive design is the design of the building's heating, cooling, lighting and ventilation systems using sunlight, wind, vegetation and other naturally occurring resources on the building site (Kibert, 2008). It includes the use of all possible measures to reduce energy consumption before considering any active systems (boilers, air conditioning, pumps and other powered systems). A successful passive design system generates a truly climate-responsive and a sustainable energy efficient building, thereby reducing the costs of heating, cooling, ventilation and lighting.

According to Kilber (2008) passive design has two main features:

- The use of building's location and site to reduce the building's energy profile;

- The design of the building itself; its orientation, fenestration, ventilation paths and other measures.

Figure 2.3 and Table 2.2 demonstrate and summarise some of the factors that should be included in the development of a passive design strategy. These factors are likely to include orientation, latitude, altitude, solar radiation, annual wind strength and direction, the presence of trees and vegetation, and the presence of other buildings.
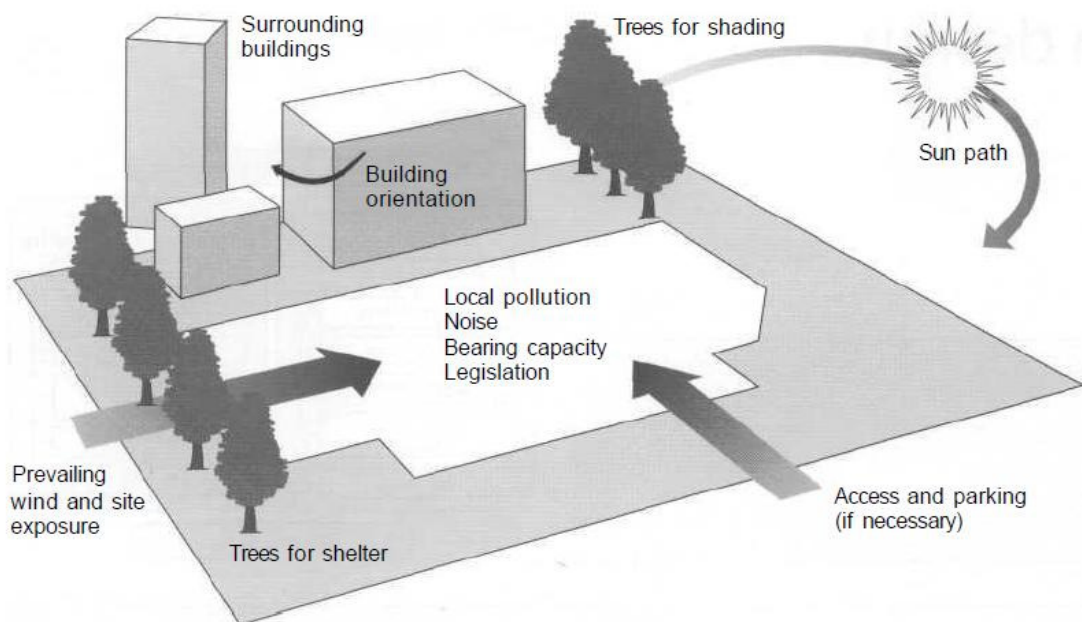
Figure 2.3 Site considerations in passive design
Source: (CIBSE, 2004)

Table 2.2 Passive design factors
Source: (Kibert, 2008)

Local climate	Latitude (lower temperatures in places of greater latitude), sun angles and solar radiation, wind velocity and direction, air temperature and humidity throughout the year.
Site conditions	Topography (e.g. slope, site views), vegetation, soil conditions, relationship of other buildings.
Building aspect ratio	Ratio of the building's length to its width. In cold climate the ratio is 1.0 (square in shape) to minimise the surface area through which heat can be transmitted. While in hot climate the aspect ratio increases with the building becoming longer and narrower to minimise the relative exposure of east and west surfaces that experience the greatest sun load.
Building orientation	Long axis oriented east-west, room layout, glazing.
Building use	Occupancy schedule and use profile
Daylighting strategy	Fenestration, daylight devices (light shelves, sky-lights, internal and external louvers)
Building envelope	Geometry, insulation, fenestration, doors, air leakage, ventilation, shading, thermal mass.
Internal loads	Lighting, equipment, appliances, people
Ventilation strategy	Cross-ventilation potential, paths for routine ventilation

Therefore, different buildings have different passive design considerations depending on their use, geometry, location, climatic and site conditions. A detailed description and explanation of each factor has been discussed in many publications such as Rennie and Parand (1998), Littlefair et al. (2000), CIBSE (2004), ICAEN (2004), CIBSE (2006), Thomas and Fordham (2006), McMullan (2007), ACE et al. (2008), Kibert (2008) and Szokolay (2008).

One of the most important factors affecting the sustainable design of buildings is the consideration of local climatic conditions and characteristics (Szokolay, 2008). Buildings were traditionally constructed to protect and provide shelter from the vagaries of the weather (ICAEN, 2004; Roaf et al., 2008). They were considered as climate modifiers which could take advantage of local weather to enhance their architectural integrity and environmental quality (Givoni, 1998; Hui and Tsang, 2005).

However, there is a mounting scientific evidence and consensus that our climate is changing (UKCIP, 2009). Undoubtedly, this change will have a crucial impact on how buildings will operate and perform. Most of the new build and current building stock will still be in use in 50 year's time and historical weather patterns will have been used to calculate building performance and energy needs (Kilsby et al., 2007). Nevertheless, it is not clear how relevant these calculations will be 50 years from now for what may be a very different prevailing climate (Sharples and Lee, 2009). Therefore, it is not possible to achieve sustainable and energy efficient buildings design without thorough understanding of how our future climate will change over the coming decades (Hui and Tsang, 2005).

2.10   Conclusion

Achieving sustainable development requires humankind to live within the limits of the environment's capacity; provide resources for human activities and subsequently absorb the pollution and waste that these activities generate. Sustainable construction, as a necessary contributing element of sustainable development in the built environment, aims to reduce the environmental impact of a building over its entire lifecycle, whilst improving its comfort and the safety of its occupant and ensuring economic viability.

As a consequence of increased global energy demands serious environmental impacts (pollution, CO_2 emissions and climate change) are becoming evident. Moreover, fossil fuels are becoming increasingly finite (and unaffordable) leading to a pressing need for the built environment to become more energy efficient. Therefore the adoption of a passive design approach, which takes into consideration climate change and its impacts, will ensure that buildings remain resilient; healthy; affordable and resource efficient.

CHAPTER THREE

CLIMATE CHANGE

3.1   Introduction

There is increasing scientific evidence that human activities are changing the earth's climate and that likely future changes present a serious threat to human society and the natural environment. Climate change is seen as a symptom of unsustainable development (Mackay, 2008). The Fourth Assessment Report (AR4) from the Intergovernmental Panel on Climate Change (IPCC) in 2007 said that "it is very likely that anthropogenic greenhouse gas increases caused most of the observed increase in global average temperatures since the mid-20th century" and more recent research has increased confidence in this statement (UKCIP, 2009, p.9). This chapter reviews climate change by examining its causes and looking at the impacts that it might have on the globe and the UK in particular. The recent responses to tackle this serious threat both internationally and within the UK are outlined with a focus on the implications for the built environment.

3.2   What is Climate Change?

According to the IPCC (2007, p.30) climate change refers to 'a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an expected period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity'. Another definition given by the United Nations Framework

Convention on Climate Change (UNFCCC), is that 'climate change relates to a change of climate that is attributed directly or indirectly to human activity that changes the components of the global atmosphere and that is in addition to natural climate variability observed over similar time periods' (IPCC, 2007, p.30).

3.3 Evidence of Changes in Global Climate and Potential Effects on Natural and Human Environment

Evidence is mounting that the global climate is changing. Records taken from millions of individual thermometers around the world since 1850 show that the global average surface temperature has risen by about 0.6°C since the beginning of the twentieth century (**Figure 3.1**), with about 0.4°C of this warming occurring since the 1970s (Hulme et al., 2002). The year 1998 was the warmest year on record, and 2001 was the third warmest while 2008 was the tenth warmest on record (Jones, 2009). Furthermore, the 1990s was the warmest complete decade in the last 100 years, and it is likely that the last 100 years was the warmest century in the last millennium (Hulme et al., 2002).
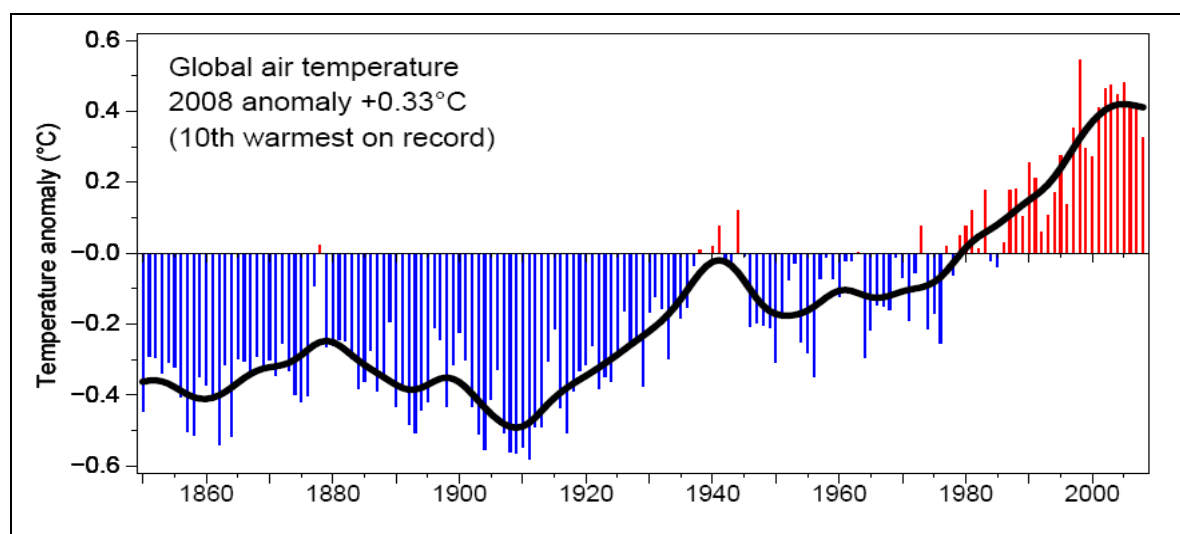
Figure 3.1 The observed increase in global-average surface temperature. Anomalies are relative to 1961-1990 average.
Adapted from (Jones, 2009)

Other evidence for changes in global climate include (Hulme et al., 2002; IPCC, 2007):

- an increase in night-time temperatures over many land areas at about twice the rate of day-time temperatures increases;

- more intense rainfall events over many Northern Hemisphere mid-to high latitude land areas and

- an increase in the sea level by about 20 cm between 1900 and 2000.

Temperature increases, changes in rainfall and drought patterns, sea level rise, and changes in storm intensities will put people's lives at risk from drought, flooding, famine and disease (Hulme et al., 2002). Moreover, climate change is likely to exacerbate current stresses on water resources from population growth and economic and land-use change, including urbanisation. Increased temperatures will affect the physical, chemical and biological properties of fresh water (IPCC, 2007). This will put more pressure on shrinking water resources which may lead to regional political tension and instability (IPCC, 2007).

In addition to the environmental and social impacts, increasing attention is being placed on the economic costs of climate change. In 2006, Stern's Review on the Economics of Climate Change was the first comprehensive UK review of the impacts of climate change on the world economy (Stern, 2006). This review evaluated widespread evidence of the impacts of climate change and on the associated economic implications and used several techniques to evaluate costs and risks. It concluded that unless strong and early actions to tackle climate change were implemented, costs in excess of 20 % of global gross domestic product (GDP) would be incurred if delayed [GDP is a basic measure of a country's overall economic output]. In contrast, the costs of these actions if have been taken now would only be about 1% of GDP (Stern, 2006).

Whatever the cause, the fact that the Earth's climate is changing is unequivocal and this change is increasingly posing a serious threat to humankind's way of life, endangering the global environment, economy and security. Therefore, understanding the causes of that change will help to reduce the risks of the threat and prepare suitable adaptation measures to deal with the consequences that cannot be avoided.

3.4   Causes of Climate Change

3.4.1   The Greenhouse Effect

A balance between energy coming from the Sun in the form of visible radiation (sunlight), and energy constantly being emitted from the Earth to space in the form of infra-red radiation determines the temperature of the Earth (Smith, 2005, HM Government, 2006). The energy coming in from the Sun can pass through the atmosphere with little direct warming effect but it warms the Earth's surface which in turn warms the atmosphere by convection and the emission of infrared radiation, which is absorbed by gases called the 'greenhouse gases' (**Figure 3.2**).

An analogy is made with the effect of a greenhouse, which allows sunshine to penetrate the glass that in turns keeps the heat in, hence the term 'greenhouse effect' (HM Government, 2006).
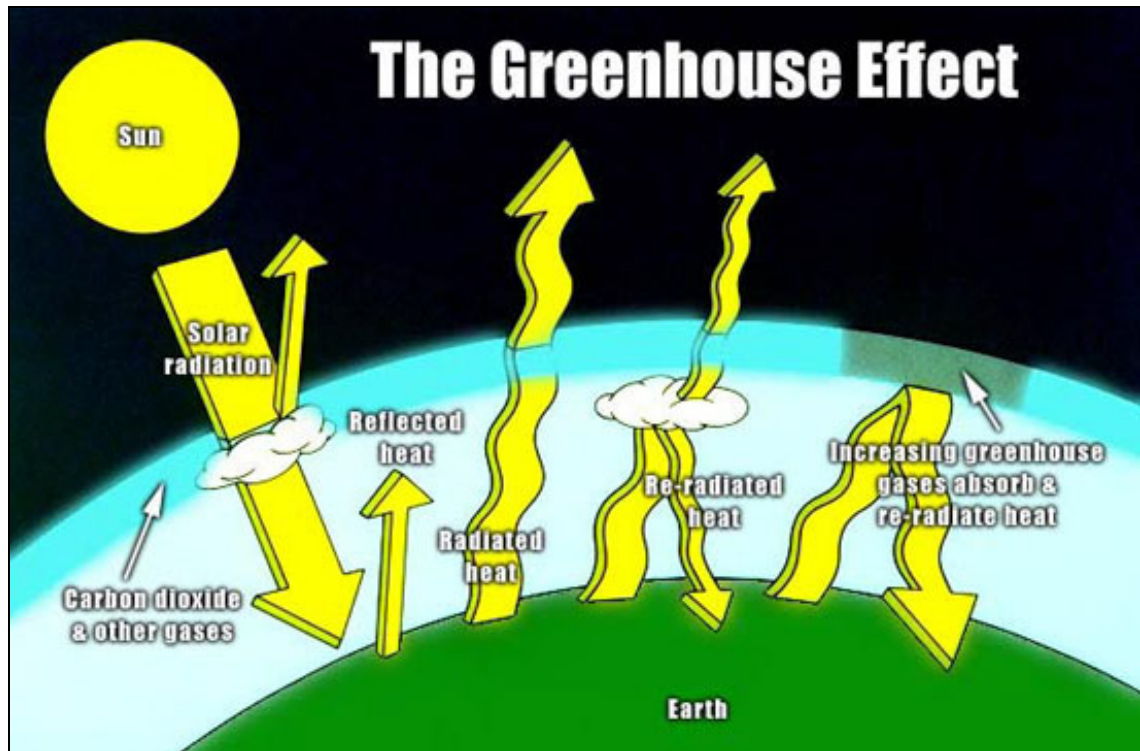
Figure 3.2 The greenhouse effect
Source: (Noel, 2007)

Smith (2005) emphasises that without this natural greenhouse effect, the Earth would be over 33°C cooler than it is and would be too cold to be habitable. He also stresses that as greenhouse gas concentrations rise well above their natural levels, the additional warming that will take place could threaten the future sustainability of the planet.

The main, naturally occurring, greenhouse gases are water-vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Hardy, 2003). Although water vapour makes the greatest contribution to the greenhouse gases, it has a short lifetime in the atmosphere and its concentration is largely determined by the temperature of the atmosphere and not simply by emission rates (Hardy, 2003).

By contrast, the other three gases have relatively long atmospheric lifetimes, (50-200 years for CO_2, 12-17 years for CH_4, 120-150 years for N_2O), and so their concentrations are determined by emission rates (Hardy, 2003). Each greenhouse gas has a different capacity to cause global warming, depending on its radiative properties, its molecular weight, its concentration and its residence time in the atmosphere (Smith, 2005). **Figure 3.3** shows the relative contribution of greenhouse gases to global warming over the next 100 years. Clearly CO_2 is the most important greenhouse gas and it is likely that it will have a significant impact on the future change in the climate.
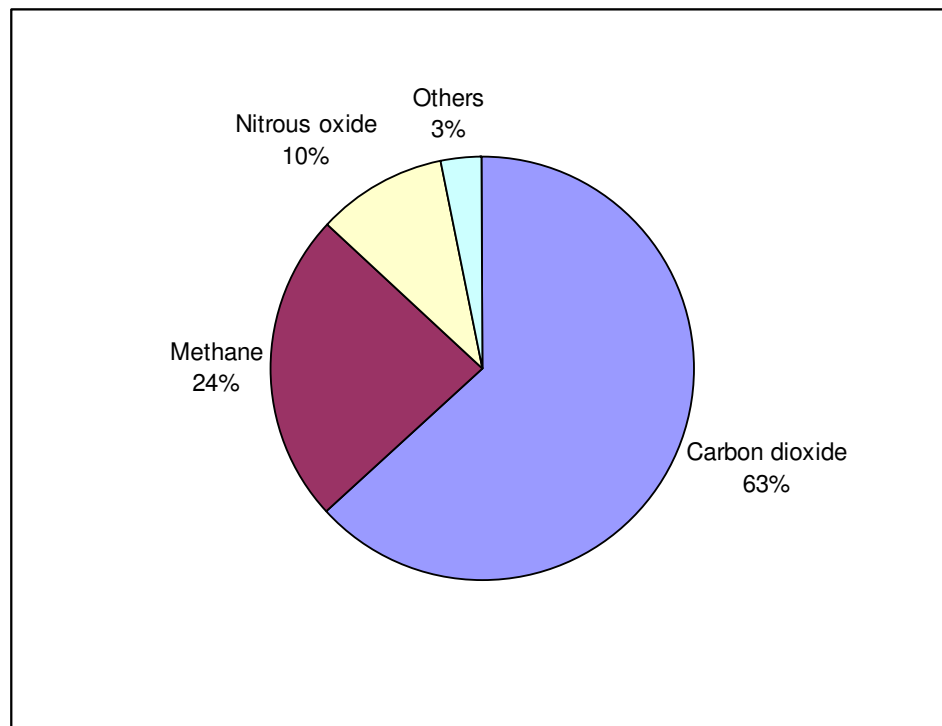
Figure 3.3 The relative contribution of current emissions of greenhouse gases to global warming over the next 100 years
Source: (HM Government, 2006)

3.4.2   Why is Climate Changing?

In order to identify the causes of recent changes in the climate, the Hadley Centre for climate prediction provided a model for simulating global climate from 1860 to 2000 considering natural factors, human factors (anthropogenic emissions of greenhouse gases) and then both sets of factors combined. Results from this model showed that only when both sets of factors were combined could the temperature rises in the mid-twentieth century and more recently since 1970s be explained (Hulme et al, 2002).

The Earth's climate varies naturally as a result of interactions between the ocean and the atmosphere, changes in the Earth's orbit, fluctuation in energy received from the Sun and volcanic eruptions (Hulme et al., 2002). Human activities such as burning fossil fuels for transport, energy generation and other purposes, along with an increase in deforestation and agriculture are likely to have significantly contributed to the acceleration rate of this natural change, particularly since the industrial revolution (Houghton et al., 2001; Hulme et al., 2002; Vivian et al., 2005). In less than 200 years the atmospheric concentrations of these greenhouse gases has been increased by some 50 % relative to pre-industrial levels (Hulme et al., 2002).

Figure 3.4 illustrates that globally, the annual CO_2 emissions have increased between 1970 and 2004 by nearly 80 % from 21 to 38 Gigatonnes (Gt) and represented 77 % of total greenhouse gas emissions in 2004 (IPCC, 2007). The largest increase in greenhouse gas emissions between 1970 and 2004 has come from energy supply followed by industry, deforestation, agriculture, transport, residential and commercial buildings, waste and wastewater (**Figure 3.5**).
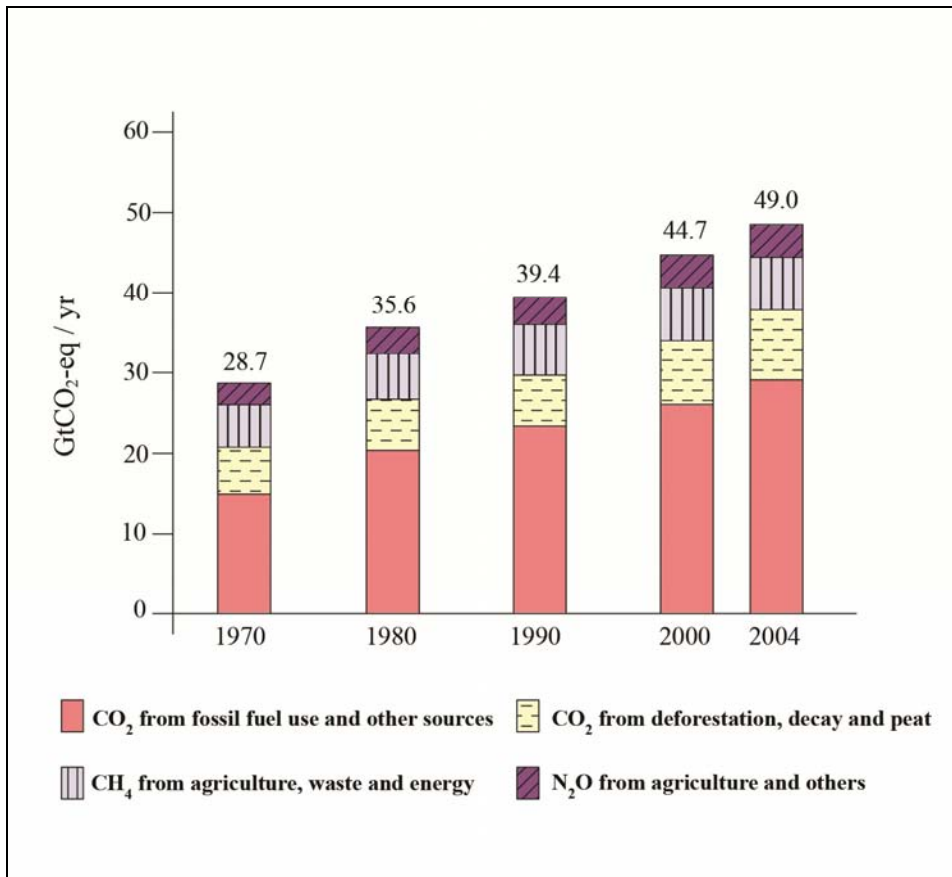
Figure 3.4 Global annual emissions of greenhouse gases from 1970 to 2004
Source: (IPCC, 2007)
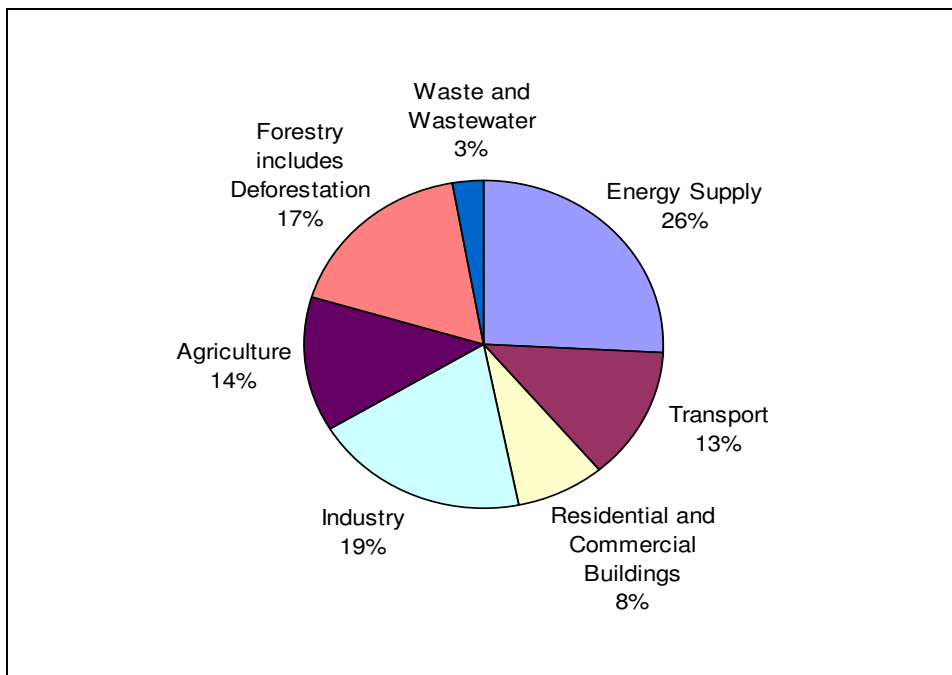
Figure 3.5 Contribution of different sectors in total greenhouse gas emissions
in 2004.
Source: (IPCC, 2007)

The additional quantities of greenhouse gases, emitted from different human activities, result in an increase in greenhouse gas concentrations. This increases the energy absorbed in the lower atmosphere contributing to changing the pattern of other climatic events including changing rainfall intensity and storm frequency (Houghton et al., 2001).

3.5   UK Climate Change

While the term 'global warming' represents the basic world-wide climate change, many more complex changes are expected in particular on the scale of regions and individual countries (Houghton, 2009). In the UK, which is located between the continental climate of Central Europe and the maritime climate of the Atlantic and influenced by the Gulf Stream, there are expected to be complex changes in temperature, precipitation and wind patterns, cloudiness and humidity, and sea level (Sanders and Phillipson, 2003).

Analysis of climate data in Central England covering the last three and half centuries shows that the surface temperature rose by about 1°C during the twentieth century and the 1990s was the warmest decade since records began in the 1660s (Hulme et al., 2002). Ten of the warmest years on record have occurred since 1990, with July 2006 being the warmest month on record, the autumn of 2006 was the warmest autumn, and April 2007 was the warmest April (Arup, 2008). August 2003 was the hottest month recording the highest peak temperature in the UK (38.5°C at Faversham, Kent) and resulted in 2,000 premature deaths in the UK (Arup, 2008). The flooding in the summer of 2007 showed the devastating impact that can result from sudden heavy downpours; this caused the flooding of 55,000 properties and left 350,000 people without mains water (DEFRA, 2009).

Other evidence for changes in the UK climate includes (Arup, 2008):

- the thermal growing season for plants in Central England has lengthened by about one month since 1900;

- heatwaves have become more frequent in summer with an increase in average duration of summer heat waves by between 4 to 16 days in all regions of the UK since 1961;

- Winters over the last 200 years have become wetter relative to summers throughout the UK;

- average sea level around the UK is now about 10 cm higher than it was in 1900.

One of the earliest climate change impact studies in the UK was undertaken by the London Climate Change Partnership (LCCP) (LCCP, 2002). **Table 3.1** summarises the main findings of the report and gives examples of how climate change could increasingly affect different aspects of people's way of life.

Table 3.1 Potential climate change impacts on the UK
Source: (London Climate Change Partnership, 2002)

Issue		Key Impacts
Higher Temperatures	⟹	Intensified urban heat island (an area such as a city or industrial site which has consistently higher temperatures than surrounding areas because of a greater retention of heat, as by buildings, concrete, and asphalt). Increased demand for cooling energy in summer. Reduced demand for space heating in winter.
Flooding	⟹	More frequent and intense winter rainfalls leading to riverine flooding and overwhelming of urban drainage systems. Rising sea levels, storminess and tidal surges require more closures of rivers barriers.
Water Resources	⟹	Increased water demand in hot, dry summers. Reduced soil moisture and groundwater replenishment. River flows higher in winter and lower in summer. Water quality problems in summer associated with increased water temperatures and discharges from storm water outflows.
Health	⟹	Poorer air quality affects asthmatics and causes damage to plants and buildings. Higher mortality rates in summer due to heat stress. Lower mortality rates in winter due to reduction in cold spells.
Biodiversity	⟹	Increased competition from exotic species, spread of diseases and pests, affecting both fauna and flora. Rare salt-marsh habitats threatened by sea level rise. Increased summer droughts cause stress to wetlands and beech woodlands. Earlier springs and longer frost-free season affect dates of bird egg-laying, leaf emergence and flowering of plants.
Built Environment	⟹	Increased likelihood of building subsidence on clay soils. Increased ground movement in winter affecting underground pipes and cables. Reduced comfort and productivity of workers.
Transport	⟹	Increased disruption to transport systems by extreme weather. Higher temperatures and reduced passenger comfort. Damage to infrastructure through buckled rails and rutted roads. Reduction in cold weather- related disruption.
Business and Finance	⟹	Increased exposure of insurance industry to extreme weather claims. Increased cost and difficulty for households and business of obtaining flood insurance cover. Risk management may provide significant business opportunity.
Tourism and Lifestyle	⟹	Increased temperatures could attract more visitors to the UK. Higher temperatures encourage residents to leave the UK for more frequent holidays or breaks. Outdoor living, dining and entertainment may be more favoured. Green and open spaces will be used more intensively.

Clearly, these changes will affect many aspects of the UK environment, economy and society including agriculture, the distribution of plants and animals, health, tourism, buildings, and the transport infrastructure. Therefore, it is crucial to understand the nature of climate change risk to be in a position to 'future proof' the lives of people for the projected range of future climate scenarios.

3.6   UK Climate Change Scenarios

While the fact that the climate is changing is beyond reasonable doubt, the precise nature of such change remains highly uncertain. This uncertainty arises from three main causes namely (Hulme et al., 2002; Jenkins et al., 2009):

- Natural climate variability (natural internal processes in the climate system such as interactions between ocean and atmosphere; natural external influences on climate such as fluctuations in energy received from the Sun and changes in the amount of particles in the atmosphere from volcanoes);

- Imperfect understanding of Earth system processes and their incomplete representation in climate models; and

- Uncertainty in future emissions of greenhouse gases and other pollutants, which depends upon how economies, population, energy technologies and societies develop.

Since at present, there is no way to forecast future changes in the activities of the Sun or volcanoes, variations in these have been excluded in future climate projections (Jenkins et al., 2009). Only natural internal processes variability in the climate and future emissions of

greenhouse gases can be predicted and therefore can be included in any future climate projections models (Jenkins et al., 2009).

The IPCC in its Special Report on Emission Scenarios (IPCC SRES) developed a range of projections of possible future emissions which in turn were based on different descriptions of how the world may develop in the decades to come (IPCC, 2000). Four of these emissions (designated B1, B2, A2 and A1F1) were chosen to cover the whole range of projection scenarios.

Figure 3.6 shows the amount of carbon emitted over the twenty-first century under each of these emissions scenarios. Summed over the century, A1F1 has the highest total emissions [2189 Gigatonnes of carbon (GtC) or 8034 Gigatonnes of CO_2 (GtCO$_2$) since 1 GtC equals 3.67 GtCO$_2$] which is more than twice total emissions of the lowest scenario, B1 [983 GtC or 3608 GtCO$_2$] (Hulme et al., 2002).
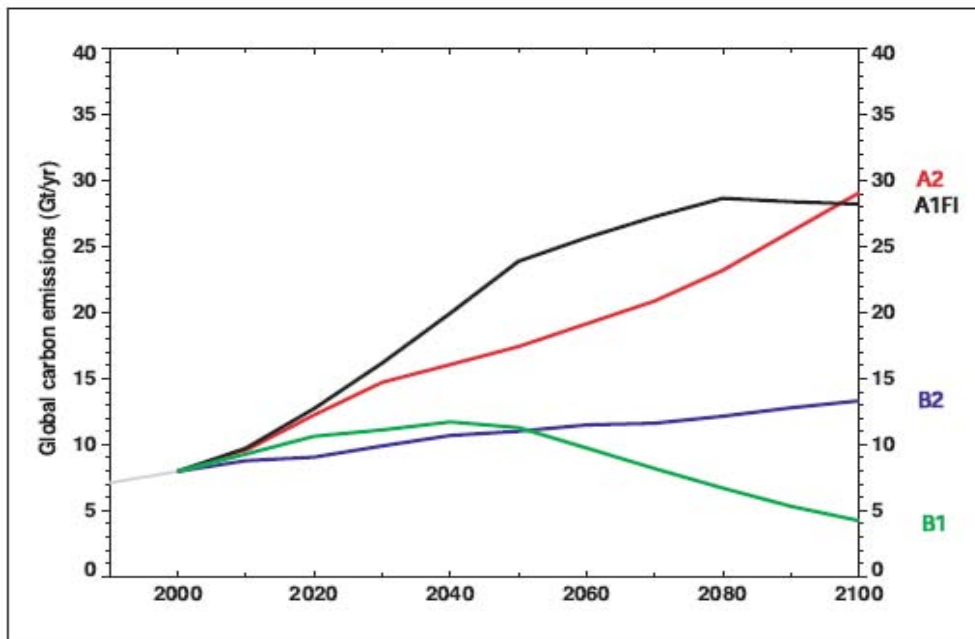
Figure 3.6 Global carbon emissions from 2000 to 2100 for the four chosen
SRES emissions scenarios.
Source: (UKCIP, 2002)

To address uncertainties in emissions of greenhouse gases and provide a common baseline over the extensive range of climate impact studies that have been carried out in the UK, the UK Climate Impacts Programme (UKCIP) developed well-defined future climate scenarios. These combine the future greenhouse gas emission scenarios report produced by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2000), with the results from the climate simulation models (run by the Met Office Hadley Centre) (Johns et al., 2001) and processing by the Tyndale Centre at the University of East Anglia, Norwich (Hulme et al., 2002, Sanders and Phillipson, 2003).

The outputs from the models provide a range of estimates of regional variations to a resolution of 50 km for various components of the climate, such as temperature and rainfall, and are given for the 2020s [the period from 2011 to 2040], 2050s [the period from 2041 to 2070] and 2080s [the period from 2071 to 2100] (Hulme et al., 2002).

 All changes in climate components (temperature, rainfall, humidity etc.) are expressed relative to a modelled 30-year baseline period of 1961-1990. Levels of confidence have also been assigned to particular qualitative statements in terms of high, medium-high, medium-low, and low which are related to the original IPCC scenarios B1, B2, A2 and A1F1 (**Table 3.2**). These confidence levels reflect the reliability of a selection of the predicted outputs (scenarios) based on the subjective opinion of the developers of the models and are not described as being scientifically accurate (Hulme et al., 2002, Vivian et.al, 2005).

Table 3.2 shows the changes in global surface temperature and atmospheric CO_2 concentration for the 2080s period for the four scenarios. Atmospheric CO_2 concentration levels are expressed in parts per million by volume (ppm). [1 ppm of atmospheric CO_2 concentration is equivalent to 2.13 GtC or 7.81 $GtCO_2$] (Clark, 1982).

Table 3.2 Changes in global surface temperature (°C) and atmospheric CO_2 concentration (ppm) for the 2080s period for the four scenarios.
Source: (UKCIP, 2002)

SRES Emissions Scenario	UKCIP02 Climate Change Scenario	Increase in Global Surface Temperature (°C)	Atmospheric CO_2 Concentration (ppm)
B1	Low Emissions	2.0	525
B2	Medium-Low Emissions	2.3	562
A2	Medium-High Emissions	3.3	715
A1F1	High Emissions	3.9	810

Global surface air temperature may increase between 2°C and 3.9°C and the associated CO_2 concentration may increase between 525 ppm (4100 $GtCO_2$) and 810ppm (6326 $GtCO_2$) depending on the developed future scenario. It is worth noting that CO_2 concentration in 1959 was about 316ppm (2468 $GtCO_2$), increased to 389 ppm (3038 $GtCO_2$) in 2009 or nearly 1.5 ppm (11.7 $GtCO_2$) per year on average (Roaf et al., 2009).

Examples of how average temperature and average precipitation, could change under different emissions scenarios are presented in **Figure 3.7** and **Figure 3.8**. These figures demonstrate that predicted mean temperature and precipitation changes vary significantly according to which scenario is adopted and on a region by region basis. The projected changes in the climate will start to become obvious by 2050s with significant changes happening by 2080s.
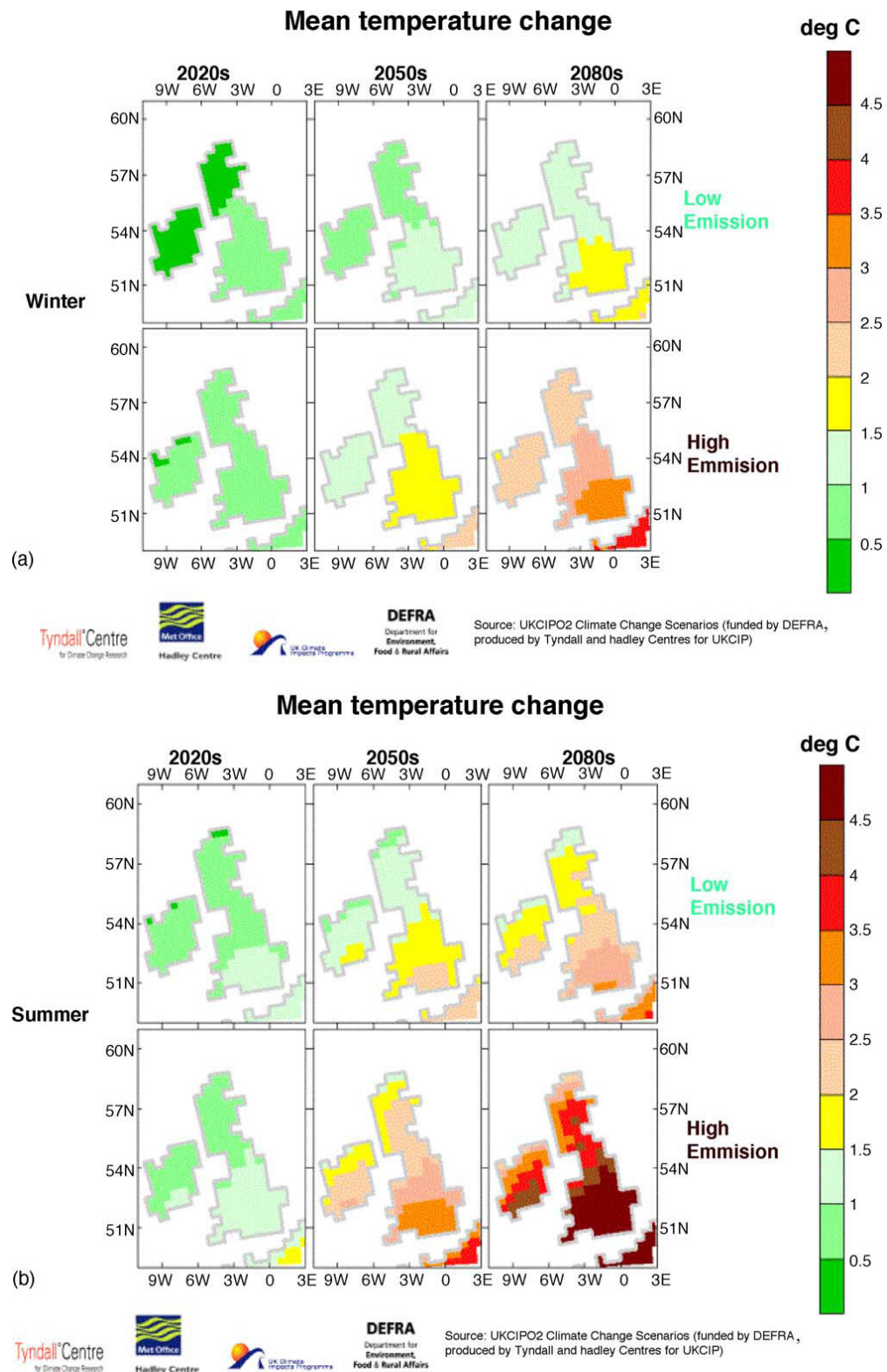
Figure 3.7 Projected changes in average summer and winter
temperature under two emissions scenarios.
Source: (Hulme et al., 2002)
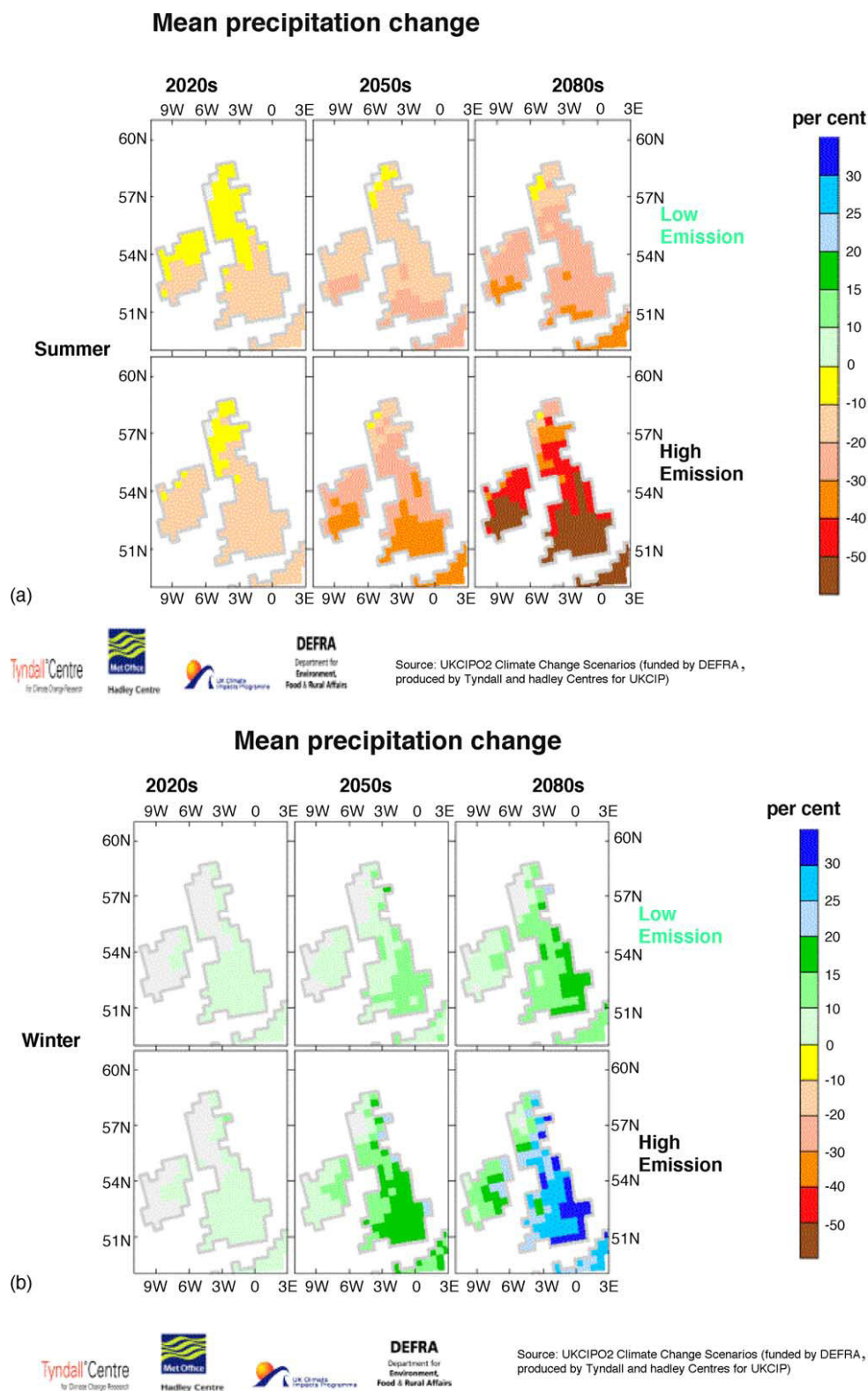
Figure 3.8 Projected changes in average summer and winter precipitation under two emissions scenarios.
Source: (Hulme et al., 2002).

Figure 3.7 shows that the average temperatures in winter and summer across the UK may rise by between 1.5°C and 3.5°C and between 2°C and 5°C respectively by the 2080s, depending on the scenario. The average precipitation in winter will increase by between 10 % and 30 % while average summer precipitation will decrease by between 10 % and 50 % by the 2080s, depending on the scenario (**Figure 3.8**).

Generally, there will be greater warming in the southeast than the northwest and there will be more warming in summer than winter. In contrast, there will be wetter winters and dryer summers in the southeast than northwest.

Based on the results from the UKCIP analysis, key projections in the future UK climate are likely to be (Hulme et al., 2002; UKCIP, 2009):

- warmer and wetter winters;

- hotter and drier summers;

- more frequent summers heatwaves;

- relative humidity will reduce;

- snowfall amounts will decrease;

- relative sea level will continue to rise and extreme sea levels will be experienced more frequently;

- the Gulf Stream may weaken in the future.

Many variables exist in modelling future climate change and it is difficult to know which scenario is more likely to occur or which event will have the greatest impact. Therefore, it is important to recognise that those scenarios do not represent the full range of potential climate change impacts; rather they simply reflect a range of plausible climate futures.

Given the range of uncertainty inherent in this kind of analysis, within both the projected emissions trajectories and the climate models employed, the relative likelihood of each scenario cannot be determined. Each is therefore considered equally likely (Gaterell and McEvoy, 2005). However, this uncertainty should not be used as an apology for not taking suitable adaptation actions to tackle climate change. Many decisions in business and politics are commonly made in the light of uncertainty (e.g. investment decisions) and deciding on the need for, and type of adaptation should be approached in a similar way. This normally involves taking a risk management approach such as that described in the UKCIP risk, uncertainty, and decision making framework (Willowsand, 2003).

In response to the increased demand for information about uncertainties associated with future climate information in order to assess the range of risks that climate change poses, UKCIP published UKCP09. Instead of the single deterministic numbers (**Table 3.2**) given in UKCIP02 which hide the uncertainty (i.e. working with fixed input parameter values and representing results as single values rather than probability ranges) (Jenkins et al., 2009), UKCIP09 presents the probability of a certain change happening within a certain time frame.

Figure 3.9 illustrates the distinction between UKCIP02 and UKCIP09 by using temperature as an example. The single approximate value for change in temperature from UKCIP02 provides no information about uncertainty. Using a range of climate models outputs would provide different changes in temperature but give no information on which to use. In contrast, UKCIP09 demonstrates a range of potential outcomes and the probability of each outcome, based on how much evidence there is for different levels of future climate change, using a developed methodology and professional judgement (Jenkins et al., 2009).
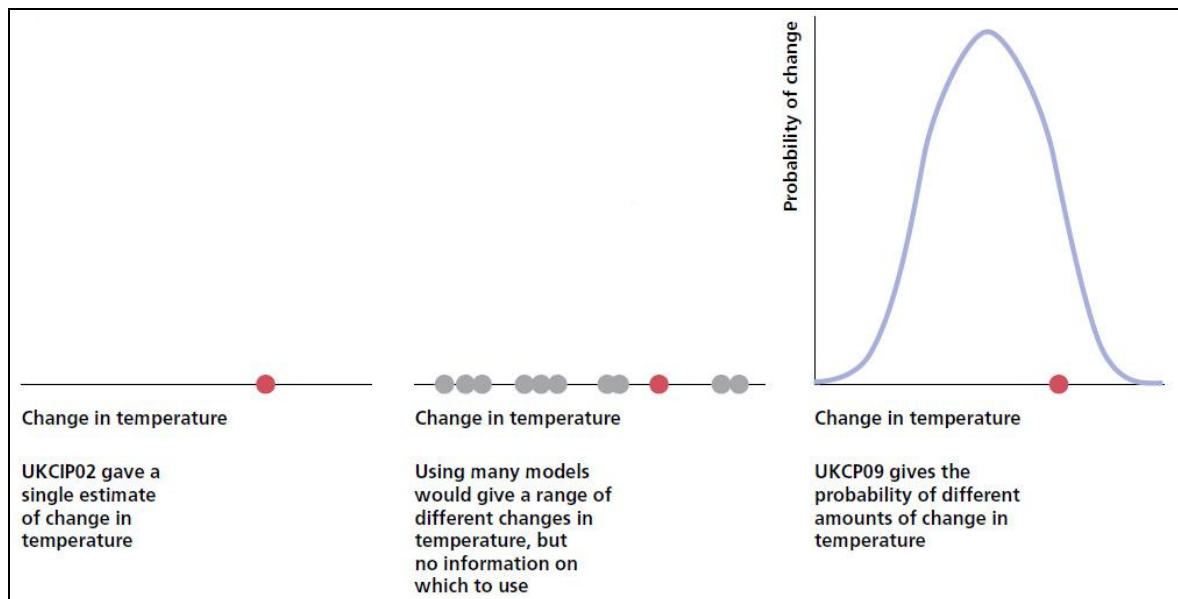
Figure 3.9 Difference between UKCIP02 and UKCIP09 using temperature as an example
Source: (Jenkins et al., 2009)

Figure 3.10 shows the projected changes to mean daily maximum temperature in summer in UKCIP09 by the 2080s under the Medium emissions scenario. The figure demonstrates that mean daily maximum temperatures increase everywhere across the UK. However, temperature increase is larger in the south and smaller in the north.

By taking the southeast area as an example (**Figure 3.11**), there is a 10 % probability [very unlikely] of the temperature rise being less than 2.3°C, a 50 % probability [as likely as not or central estimate] being less than or exceeding 5.3°C and a 90 % probability [very likely] being less than 9.2 °C.
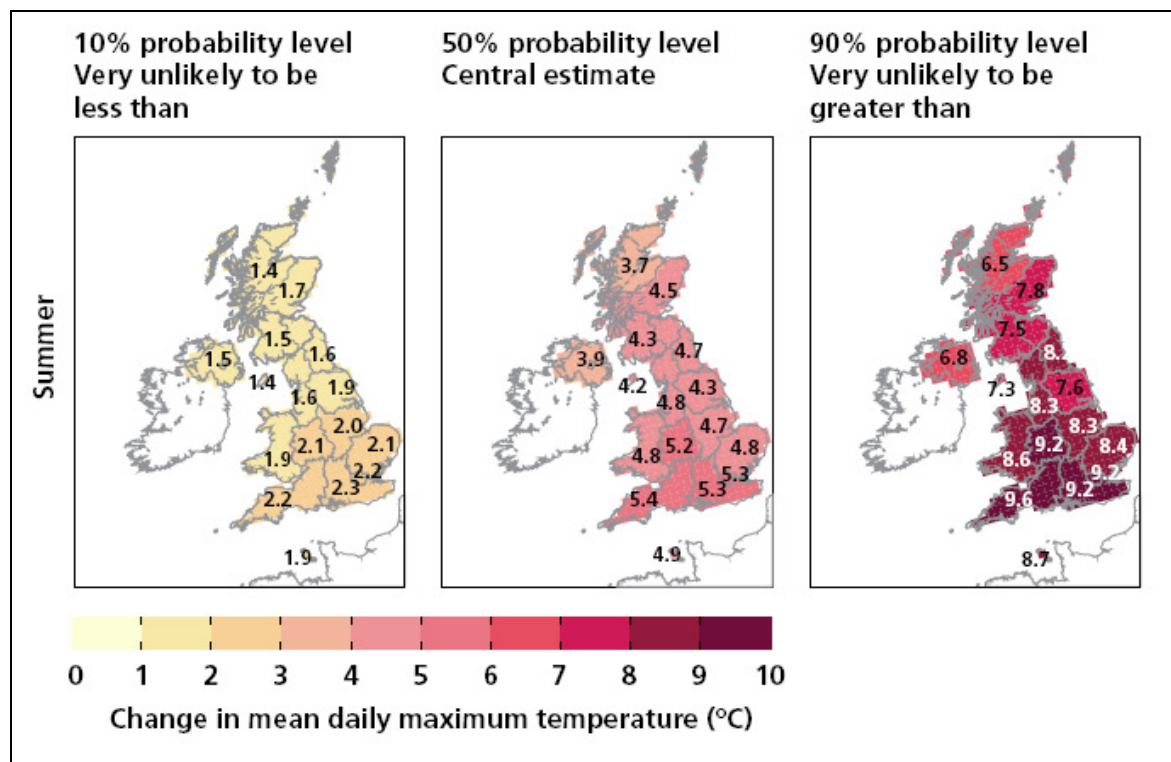
Figure 3.10 10, 50 and 90 % probability levels of changes to mean daily maximum temperature in summer by the 2080s, under the Medium emissions scenario. Source: (Jenkins et al., 2009)
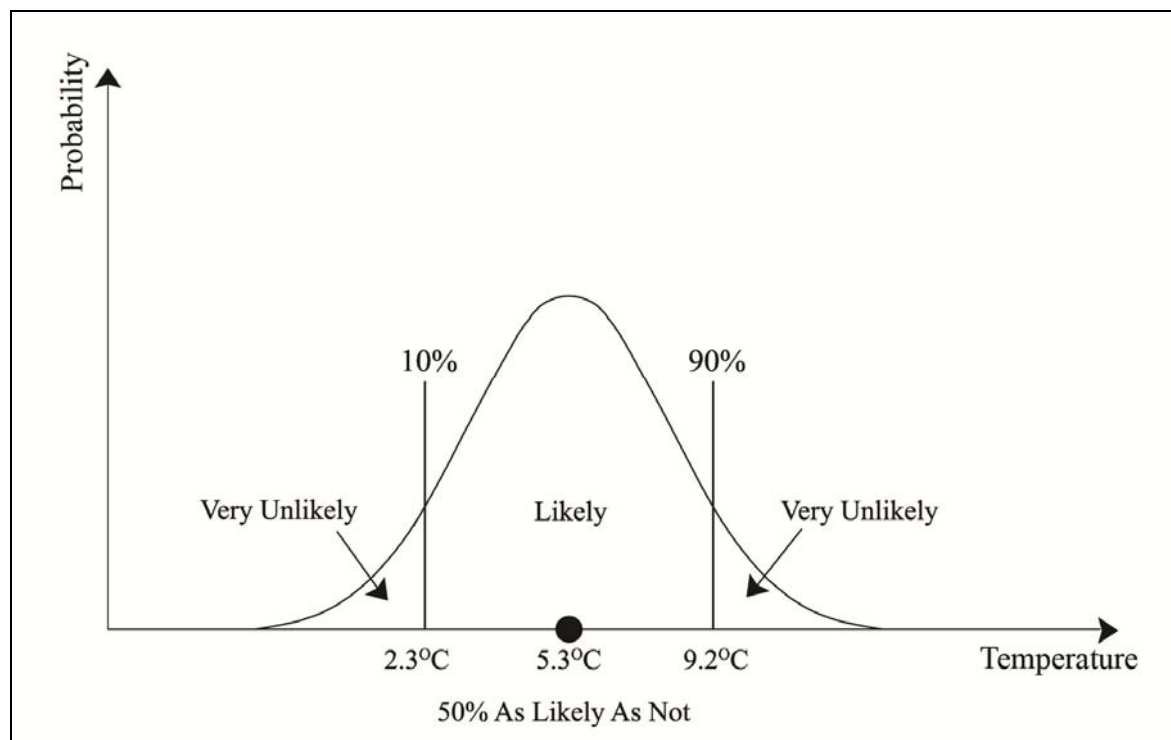
Figure 3.11 Probabilistic levels of changes to mean daily maximum temperature in summer by the 2080s, under the Medium emissions scenario for the southeast of England. Source: (Jenkins et al., 2009)

The UKCIP09 projection is more robust since it describes the degree of uncertainty in the scenario in probabilistic terms allowing risk assessment to be investigated for seven overlapping 30-year periods (2020s, 2030s, 2040s, 2050s, 2060s, 2070s, 2080s) and for three different future emission scenarios (Low, Medium, and High) (Jenkins et al., 2009). Similar to UKCIP02, all changes in different climate variables (temperature, precipitation etc.) are expressed relative to a modelled 30-year baseline period of 1961-1990.

It is worth noting that the results of this new set of projections are broadly consistent with the previous set, UKCIP02. However, there is a lot more information in UKCIP09 and wider ranges in the new set of projections (UKCIP, 2009; DEFRA, 2009).

3.7   Actions to Reduce Climate Change

Climate change is a global problem with global causes and effects (Hardy, 2003). Reducing greenhouse gas emissions and dealing with the effects that cannot be avoided require efforts by all countries around the world. These efforts should consist of each country's responsibility for greenhouse gas emissions, its capability to take actions and the impacts it will experience (IPCC, 2007).

3.7.1   International Actions

In response to the climate change threat, the UNFCCC was agreed at the Earth Summit in Rio de Janeiro in June 1992 (Halliday, 2008; UNFCCC, 2010a). In December 1997, developed countries agreed at Kyoto to legally binding targets which will reduce their emissions by 5.2 % below 1990 levels over the period 2008-2012 (Munasinghe and Swart, 2005). The Kyoto Protocol came into force in February 2005 and to date has been ratified by 190 countries (UNFCCC, 2010a).

The European community and its member states agreed to an 8 % reduction by 2012 (DEFRA, 2007a). The Protocol also set up mechanisms to assist in meeting Kyoto targets in the most efficient and cost-effective manner. These mechanisms are international emissions trading, Joint Implementation (JI) and the Clean Development Mechanism (CDM), by which credits from emission reducing projects in one country can be used to meet the Kyoto target of another country. Under JI, projects can be hosted in developed countries, and under CDM, in developing countries (HM Government, 2006).

In 2009, the United Nations Climate Change Conference commonly known as the 'Copenhagen Summit' was held (UNFCCC, 2010b). The purpose of the Summit was to agree a framework for climate change mitigation beyond Kyoto Protocol commitments which end in 2012 (UNFCCC, 2010b). The Summit endorsed the continuation of the Kyoto Protocol and recognised the importance of taking actions to maintain any future temperature rises below 2°C. However, the agreement did not contain enforceable commitments for reducing emissions that would be essential to prevent any increase in temperature beyond 2°C (UNFCCC, 2010b).

3.7.2   UK Actions

In the UK, The UK Climate Change Programme was launched in 2000 by the British government to cut greenhouse gas emissions in the UK. Currently, the UK is the world's seventh largest producer of man-made CO_2 emissions emitting around 570 million tonnes or 2 % of the total generated from fossil fuels (DEFRA, 2009).

Under the Kyoto Protocol, by 2008-2012 the UK must reduce its emissions by 12.5 % from a baseline target set in 1990 (DEFRA, 2009). In November 2008, a climate change bill was

introduced which commits the UK to reductions in CO_2 emissions of at least 26 % by 2020 and a long term goal of an 80 % reduction by 2050 (Mumovic and Santamouris, 2009). The UK became the first country to set such a long range and significant carbon reduction into law (DEFRA, 2009). Furthermore, it introduces a new statutory body, the Committee on Climate Change to provide expert advice and guidance to government on achieving its targets (Mumovic and Santamouris, 2009).

The Government's plan for tackling climate change has four principles (DEFRA, 2009):

- protecting the public from immediate risk by increasing flood protection, coastal erosion management, and efficient use of water and health contingency plans;
- preparing for the future by, for example, changing the way we build and refurbish our houses and infrastructure and developing new ways to do business;
- creating a low carbon economy by making fundamental changes to decarbonise the UK in a way which maximises business opportunities, treats people fairly and keeps energy supplies safe and secure; and
- supporting individuals and businesses to play their role by working with all groups in society to support those already doing their part and to encourage others to start.

Reducing the risks that climate change may present requires both actions that reduce the build up of greenhouse gases in the atmosphere to slow the rate of change (mitigation) as well as making adjustments in policies and practices that take a changing climate into account (adaptation) (Larsson, 2003).

The UK government, through the UK climate change programme, proposes details of where different mitigation and adaptation actions could be taken to achieve carbon reduction

targets, and is being encouraged by several government policies in the following sectors: energy, business, transport, domestic, agriculture, forestry and land use, and the public sector (HM Government, 2006).

It should be noted that the climate change programme and the different adaptation and mitigation actions embedded in it have been developed within wider policy frameworks set by the government and the devolved administration e.g. (the UK sustainable development strategy) to ensure synergies and avoid conflicts with other dimensions of sustainable development (HM Government, 2006; IPCC, 2007).

3.8   Impacts of Climate Change on the Built Environment in the UK

Potential changes in the UK climate are likely to have a range of impacts on the built environment (Wilby, 2007). **Table 3.1** (page 46) gives examples of how climate change could increasingly affect the integrity of the built environment.

The most important consequence of climate change on the built environment concerns the impact of higher temperatures on thermal performance (Wilby, 2007). According to Gaterell and McEvoy (2005a) two climate parameters are important in terms of thermal comfort, heating degree days and cooling degree days.

Heating degree days (HDDs) are defined as the cumulative number of degrees in a month or a year by which the mean external temperature is below a base temperature and are used to determine space heating requirements (CIBSE, 2006). Conversely, cooling degree days (CDDs) is the cumulative number of degrees in a month or a year by which the mean external temperature exceeds a base temperature and is used to determine cooling energy loads (CIBSE, 2006). Clearly, under future climate change scenarios these values are likely

to vary considerably and as the climate warms the number of HDDs decreases and the number of CDDs increases. Anticipated numbers of HDDs and CDDs under different UKCIP02 scenarios are shown in **Table 3.3**.

These changes in HDDs and CDDs as a result of climate change will respectively decrease the energy demand required for space heating in buildings and increase the energy demand required for space cooling. The amount of the reduction in heating energy demand or the increase in cooling energy demand depends mainly on the amount of temperature change in the climate scenario, the thermal properties of the building envelope and the adjustments allowed in the building stock over time (Wilbanks et al., 2008).

At present, the majority of buildings in the UK are naturally ventilated (Hacker et al., 2005). As the outside temperatures become higher as a result of changing climate, the potential to provide cooling with comfort using external air will be less effective.

Table 3.3 Anticipated numbers of HDDs and CDDs under different climate change scenarios by 2050
Source: (Gaterell and McEvoy, 2005a)

	Projected number by 2050[a]	
	Low emission scenario	**High emission scenario**
HDDs[b]	1785- 1955	1575- 1725
CDDs[c]	Up to 80	Up to 150

[a] Based on climate conditions in South East England.
[b] Developed from a 15.5 ℃ base.
[c] Developed from a 22 ℃ base.

An obvious solution to reduce uncomfortable hot indoor temperatures is the use of air conditioning systems. However, this solution is unfavourable since it will increase energy consumption of buildings and hence CO_2 emissions that are causing climate change (Hacker et al., 2005).

It is likely that the overheating of buildings in summer and the associated thermal discomfort will be an increasing problem because of climate change. Therefore, there is a need to adapt the current building stock to minimise thermal discomfort, reduce energy costs and CO_2 emissions using passive design and low carbon energy methods.

3.9   Opportunities in the Existing Stock: Mitigation and Adaptation

Reducing the risks that climate change may pose in the built environment requires different mitigation and adaptation options to be implemented effectively. The way in which buildings are designed and used is crucially important to achieve that goal (Wilbanks et al., 2008).

So far, efforts to address climate change in the built environment have focused primarily on actions and measures for climate change mitigation by making buildings more energy efficient and reducing greenhouse gases (Steemers, 2003). But this is only half of the picture. Regardless of our actions to reduce greenhouse gas emissions we are likely to already be committed to a change in our climate as a result of our past actions.

There is an increasing concern about climate change adaptation associated with the existing building stock, which is currently one of the single biggest sources of energy consumption and associated CO_2 emissions in the UK (Steemers, 2003). The existing building stock accounts for about 50 % of total UK energy consumption while nearly 50 % of all UK

carbon emissions can be attributed to energy use in buildings for heating, cooling lighting and ventilation (Sorrell, 2003; Halliday, 2008).

In the UK, 85 % of domestic buildings which were constructed before 1985, when energy efficiency was first introduced to the Building Regulations, are on average, energy inefficient (DCLG, 2007a; HM Government, 2008). The percentage of energy inefficient non-domestic buildings is difficult to estimate due to the absence of reliable data (RIBA, 2009). However, it is widely recognised that the overall picture is likely to be little different from that in the domestic buildings (Bell, 2004).

The average rate of replacement of the existing stock in the UK is approximately 1 % per year which means that around two thirds of the building stock that will be standing in 2050 has already been built (RIBA, 2009). Consequently, widespread adaptation of this existing stock is essential to ensure that they remain comfortable, energy efficient and fit for purpose in the present and the future under different climate change scenarios (Arup, 2008).

In line with the ambitious UK target to reduce built environment carbon emissions by up to 11.7 million tonnes per year by 2020 (DTI, 2007), improving the energy efficiency of the existing stock through refurbishment will play a vital role in achieving this aim and delivering low carbon buildings. Refurbishment of buildings as an adaptation strategy in the face of climate change will be required to minimise energy use, maximise winter indoor temperatures and minimise indoor temperatures during heat waves.

Clearly, the existing buildings are of a particular concern. However, it is worth noting that in the context of climate change scenarios, typically spanning this century, new buildings will have an increasingly important role as older buildings are replaced. Within the next 50 years

one might expect half the existing buildings to have been replaced (assuming a replacement rate of 1.0 % annually) (Steemers, 2003). It is evident that climate change and its implications will need to be reflected in future building design and refurbishment.

3.10   Conclusion

Climate change is one of the most pressing environmental, social and economic problems facing the planet today. There is now a widespread scientific consensus that human activities are the principal cause. Avoiding dangerous climate change requires immediate and sustained global action. Different agreements, policies and actions have been set up both globally and within the UK to reduce the greenhouse gas emissions and to adapt for the unavoidable climate change impacts in different sectors.

The climate change scenarios developed by UKCIP represent an important step forward in understanding the nature of climate change and how to respond to it. It is designed as a base for several climate change studies so that public and private organisations can assess the likely impacts on their core activities, planning processes and investment decisions.

Climate change will have a significant impact on the built environment. It will affect summertime thermal comfort in buildings and the energy use associated with heating and cooling systems. Existing buildings need to be able to withstand the impacts of climate change over the next 50-80 years to guarantee their long term sustainability.

It is widely recognised that making significant reductions in carbon emissions from the built environment will require significant improvement to the energy efficiency of the existing stock. Therefore, it is important to look towards the future, analyse how existing buildings will cope with the changes in the climate using UKCIP scenarios and take appropriate

actions to make these buildings more energy efficient and resilient. This will help delivering sustainable buildings that reduce operating cost, improve comfort levels and increase occupant satisfaction as well as achieving significant reductions in CO_2 emissions.

CHAPTER FOUR

HIGHER EDUCATION BUILDINGS

4.1   Introduction

Higher Education Institutions (HEIs) have a central role in contributing to the agenda for sustainable development, not only through the development and delivery of an appropriate curriculum but also through the management of their estates (HEPS, 2004).

The significance of the HEIs estate, which in England comprises approximately 25 million m^2 of gross space (HEFCE, 2004), is acknowledged in the development of a strategy for sustainable development in the higher education (HE) sector (HEFCE, 2005). This strategy makes clear that the performance of the HEI estate is an essential factor in delivering sustainable development and outlines plans to consider modifying capital funding procedures to encourage the use of sustainable construction practices.

Institutions are under a range of pressures to reduce their building energy use, carbon emissions and improve the energy efficiency of their building stock. *Securing the Future* - central government's latest sustainable development strategy makes it clear that climate change, the sustainable use of natural resources and development of renewable technologies need to be central to decisions taken throughout the sectors including HE (UKSDS, 2005).

Many statutory instruments and voluntary agreements have been put in place that will help guide the HE sector towards reducing energy consumption and carbon emissions (HEEPI,

2008). These include the International Kyoto Protocol, the Climate Change Levy: a form of energy taxation for which HEIs are liable; the EU Emissions Trading Scheme which requires all organisations (including HEIs) to measure and report on their CO_2 emissions and set targets for reductions; and UK Building Regulations which set increasingly rigorous standards for efficiency, monitoring and reporting for new and existing buildings (HEEPI, 2008).

Decision making in the built environment, where asset lives of between 50 and 80 years (DEFRA, 2007a; de Wilde et al., 2008) are not uncommon, is beset with uncertainty. For example, increasingly unpredictable energy prices are likely to have a significant long-term impact on the economic viability of different building types. For UK HEIs, projected changes in energy prices, forecast in September 2005, were predicted to result in an additional £60 million to £70 million in energy costs for the financial year 2005/2006 (AUDE, 2005). The variability in energy costs emphasises the risks imposed by energy consumption and the importance of energy efficient buildings.

The implementation of effective sustainable construction practices requires uncertain pressures to be evaluated systematically. This is already recognised in the development of a toolkit by the Association of University Directors of Estate (AUDE) which seeks to provide assistance to Directors of Estates and their teams to make a prudent decision on whether to refurbish or to demolish and rebuild a very large proportion of HE stock which was built in the 1960's (AUDE, 2008).

It is important to recognise that delivering solutions that are deemed to be sustainable under current conditions is only the start. To ensure such solutions remain effective over their life time, their ability to adapt to different levels of uncertainty needs to be understood.

For example, the whole-life performance of buildings, particularly their reliance on fossil fuel based heating and cooling energy is, in part, dependent on working with prevailing climate conditions. However, while the fact that the global climate is likely to change over the coming decades is beyond reasonable doubt, the precise nature of that change remains highly uncertain (Hulme et al., 2002; UKCIP, 2009).

In the UK, projections suggest there is a range of equally plausible, but very different, climate conditions that could prevail in 50 years time (UKCIP, 2009) which could have significant impacts for the performance of non domestic buildings (Hacker et al., 2005). The HE sector is no exception to this.

This chapter reviews the current state-of-the art with regard to assessing the sustainability of refurbishments or redevelopment strategies in the HEIs and investigates the potential impacts associated with climate change uncertainty.

4.2   Higher Education Stock

4.2.1   Overview

HE in the UK is a growing sector, with student numbers increasing by a factor of 5 over the last 30 years (Carbon Trust, 2007; Universities UK, 2008). This means that the energy consumption of colleges and universities is also growing and leading to increased emissions of CO_2.

In 2004, there were 171 HEIs in the UK: 133 are located in England, with 20 in Scotland, 14 in Wales and 4 in Northern Ireland (Fawcett, 2005; Universities UK, 2008); with total staff numbers estimated at 330,000 and 2.25 million students (HEFCE, 2005).

In England, the total gross floor area is nearly 25 million m^2 or 18.6 million m^2 of the net space area [the total usable floor area in a building excluding the area occupied by walls, columns, partitions, circulation (where people walk) and mechanical equipments](Carbon Trust, 2007; HEFCE, 2007). This accounted for 0.04 % of the total number of non domestic building stock premises and 2.9 % of the floor area (Bruhns et al., 1997).

According to the Convenor of the Environmental Association for Universities and Colleges (EAUC), the environmental impact of the universities and colleges of HE in the UK is enormous (EAUC, 1998). The sector spends in excess of £15.4 billion annually on goods and services, consumes £200 million worth of energy annually or 7,771 million kWh per year, uses 31 million m^3 of water annually and owns 20 % of all UK office space (HEFCE, 2007).

The most common greenhouse gas from HE activities is CO_2 released as a product of the combustion of fossil fuels. Direct emissions are those that occur from activities owned wholly or in part by the university. These include the emissions resulting from the combustion of fossil fuels for heating buildings, hot water and powering the university vehicle fleet. Indirect emissions are released from source not owned by the university but occur as a result of university activities. The major indirect emissions result from the purchases of electricity generated by a third party (Rappaport and Creighton, 2007).

Other indirect sources include emissions resulting from the commuting population of staff and students to and from the university, from deliveries, and from university related travel on trains, buses, and aircraft. Indirect emissions also include those associated with the construction or refurbishment of buildings and the emissions associated with all materials used and purchased by the university. These include emissions associated with the

production, transport and final disposition (e.g. reuse, recycle, or disposal) of goods and waste products (Rappaport and Creighton, 2007).

The HE sector is facing up to the major problems of ageing buildings and facilities. The overall condition of the estate is now improving, but the problems being identified in particular types of buildings are such that the overall cost estimate of backlog maintenance has risen by 41 % since 2000 (Universities UK, 2008).

Most post-war HE buildings perform poorly on energy efficiency compared to modern buildings [light weight construction, single glazing, large window areas, poor insulation, and limited Heating, Ventilating and Air-Conditioning (HVAC) control] (Parkes, 2001; AUDE, 2008). Some HE buildings are gaining listed status (e.g. East Anglia and Sussex), which can constrain what can be achieved through refurbishment and modification (English Heritage, 2007).

According to Estate Management Statistics (EMS), 40 % of the HEIs in England were built between 1960 and 1979 (AUDE, 2008). **Figure 4.1** shows the percentage of non-residential build by era within the HE sector. A 2002 report commissioned by the Higher Education Funding Council for England (HEFCE) found that the HE sector faced a £3.5 billion repairs backlog (HEFCE, 2004).
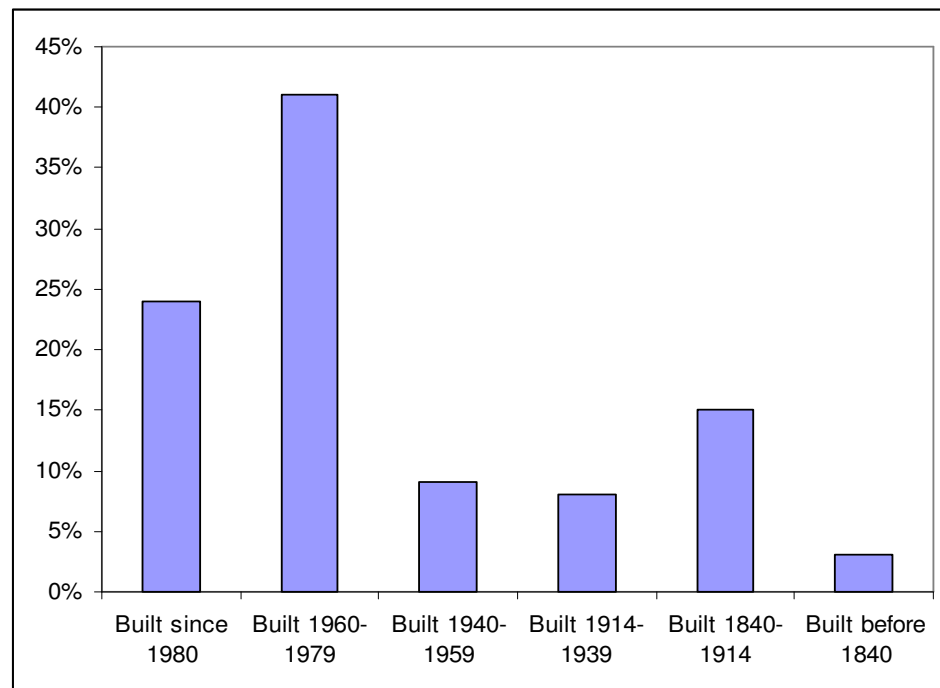
Figure 4.1 Percentage of non-residential build by era in the HE sector
Source: (AUDE, 2008)

Space requiring backlog maintenance currently stands at 8.4 million m^2, around one-third of the total space (Universities UK, 2008). A conservative estimate of the replacement cost of all 1960's building within English HEIs is approximately £11 billion, excluding demolition and disposal costs (AUDE, 2008).

HEIs have some hard decisions to take, including replacing poor buildings with more sustainable ones, and raising the finance to invest in the future (AUDE, 2008). However, improving the sustainability of its estate will enhance the environmental credentials of an HEI, which could influence the number and the capability of students attracted and retained. It would also provide reputational benefits, enhance learning environments and improve comfort conditions which can boost student productivity, morale and reduce absenteeism and health problems (Carbon Trust, 2007).

Moreover there is an opportunity to sell the social responsibility elements of energy management to current and prospective students, enhancing curricular activity and encouraging future generations to help to minimise climate change (Carbon Trust, 2007).

4.2.2   Refurbishment versus New Build

Building activities can be classified as either new build or refurbishment. New build as it is known is applied to any work that is starting from scratch. Refurbishment in one broad definition is any work undertaken on an existing building. According to Riley and Cotgrave (2005, p.6) refurbishment can be defined as:

"Extending the useful life of existing buildings through the adaptation of their basic forms to provide a new or updated version of the original structure"

Refurbishment schemes can take many forms and may be undertaken for a variety of reasons. Refurbishment can therefore be taken to mean that the existing building is not usable in its present from or state. A building could have been very well maintained but not meet the performance criteria of the existing or planned occupier or very little maintenance may have been undertaken (Mulligan and Steemers, 2002).

Figure 4.2a below illustrates where the refurbishment phase of a building fits into the whole life cycle of the building. The diagram does not show a specific time when refurbishment is required, as this may depend on the level of maintenance that has been undertaken during the occupation of the building; nor does it give actual values of performance requirement (Riley and Cotgrave, 2005).
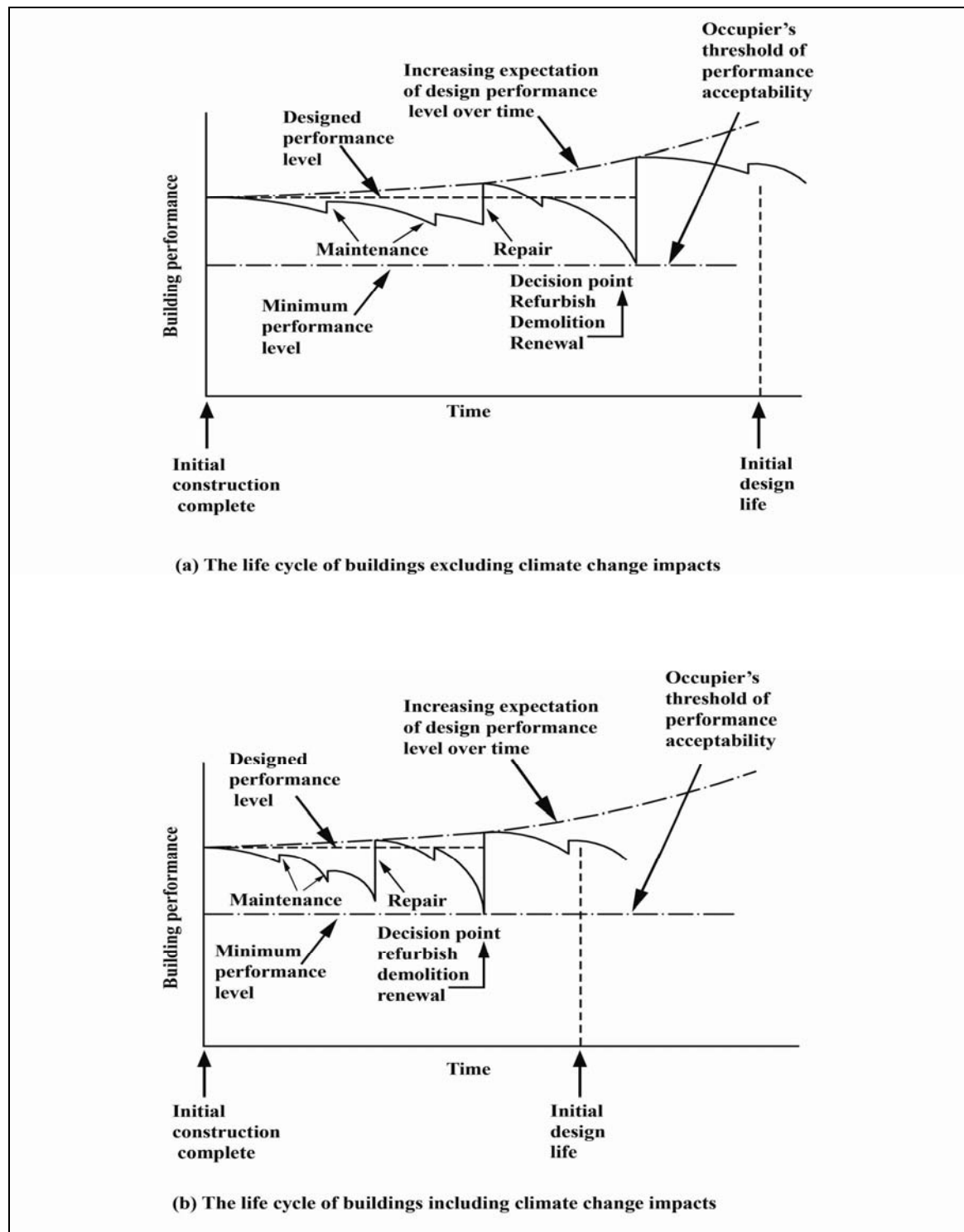
Figure 4.2 The life cycle of buildings: (a) excluding climate change impacts (b) including climate change impacts
Source: (Riley and Cotgrave, 2005)

However, Mulligan and Steemers (2002) suggest that cycles of refurbishment range typically between 15-50 years for non structural building fabric (roof, wall cladding, windows, joinery and insulation) when upgraded to higher performance levels and between 7-15 years for systems and appliances which could enable improved controls and environmental performance.

It is likely that climate change and its thermal discomfort consequences in naturally ventilated buildings will shorten the useful lifetime of these buildings and reduce their performance before any required refurbishment will be undertaken to improve such performance (**Figure 4.2b**).

The amount of work that is required to achieve the above definition of refurbishment will vary on different projects, and generally depends on many factors such as (Riley and Cotgrave, 2005):

- The state and condition of the existing building;

- The size and form of the existing building;

- The location of the building;

- The intended use of the building;

- The amount of work required for the existing building to comply with the current building regulations;

- Whether the building is listed either wholly or partly;

- Adequate funding being available; and

- Whether the work can be carried out safely.

There are many terms that are usually used instead of or in conjunction with refurbishment (Riley and Cotgrave, 2005):

- *Conversion* implies that the main use of the building will be altered, but that the main structure will not be changed;

- *Renovation and Restoration* consists of renewal and repair only, and simply addresses dilapidations to avoid further degradation of the building;

- *Retrofit* means fitting new and more modern systems into an existing building. The term is commonly associated with building services because a common phenomena in buildings is that the life of the building structure and fabric is considerably longer than that of the installed services.

From the above definitions it can be seen that refurbishment could include all of these elements on either a large or a small scale.

Refurbishment of HE buildings primarily concerns physical (envelope such as walls, windows, doors) and functional building components (e.g. mechanical and electrical equipments), but should also consider several topics such as energy consumption, pollutant emission, and operational waste reduction as well as air quality and spatial comfort (Genre et al., 2000). Refurbishment can reduce energy consumption and improve the indoor climate through better control of heating and improved building insulation.

While the fact that the cost of refurbishing some HE buildings would be about 80 % of the cost of new building, refurbishment can be more environmentally friendly than demolishing

and replacing old buildings (AUDE, 2008). This has been supported by a recent study undertaken by AUDE which investigated HE buildings. Results from this study suggest that refurbished buildings have smaller embodied environmental impacts than buildings that are demolished and rebuilt (AUDE, 2008). **Table 4.1** lists the advantages of refurbishment compared with demolition and new build. The listing of a building by regulators when viewed in conjunction with programme requirements can prevent any serious consideration of demolition and replacement: planning approval might be denied; an unacceptable delay when planning approval is sought; or planning approval may be granted with onerous conditions.

Table 4.1 The advantage of refurbishment compared with demolition and new build
Source: (Anon, 2005)

Shorter Timescales	The work involved in refurbishment is normally less than that needed for demolition and new construction. There are time savings too at the pre-contract design and planning stages.
Economic Advantages	The cost of refurbishment and reusing existing buildings is generally considerably less than the cost of demolition and new construction. These advantages have been categorised by the shorter contract duration which reduces the effects of inflation on building costs, and the shorter development period reduces the cost of financing the scheme.
Architectural Advantages	There are often architectural advantages in keeping older and historic educational buildings to satisfy heritage conservation and the perception that new buildings can in no way duplicate the structural and unique architectural qualities of the old.
Environmental Advantages	Refurbishment can reduce energy consumption and CO_2 emissions through recycling, re-using existing sources, and avoid the need to extract new materials and convert them into a replacement building. Refurbishment is significantly less intrusive and disruptive of the environment.

The consequences of listing, therefore, can justify focusing on the potential of refurbishment option rather than demolition and replacement. Similarly, where planning restrictions are unlikely to allow an increased footprint area or restrict the height of a new development, it can result in there being no net gain in accommodation space when demolition and re-building is considered. Consequently, it is often more sustainable to refurbish and re-use existing buildings than to demolish and build anew (BRE, 2002; AUDE, 2008).

There is a tendency nowadays within the HE sector to choose refurbishment over demolition and new build due to recognition of the advantages outlined above. Considerable sums of money are currently being spent on refurbishing parts of the HEI estate. Examples include: East Anglia has spent £8.6 million refurbishing its Ziggurat residences designed by Sir Denys Lasdun (Stothart, 2008), and the refurbishment of Muirhead Tower at the University of Birmingham which was completed in 2009 was estimated to have cost more than £25 million (Associated Architects, 2007). Clearly, it is essential to ensure such capital expenditure contributes to achieving the sustainable development agenda.

4.2.3   Energy Consumption in the HE Sector

Data on energy consumption and energy efficiency opportunities in the public and commercial sectors in the UK is generally much poorer than that for the manufacturing and domestic sectors (Sorrell, 2003). This is partly due to the lack of research, but also reflects the very wide range of building types in the sector and the extremely diverse activities that occur within them (DETR, 1998; DTI, 2002; Sorrell, 2003). The HE sector is no exception to this.

Table 4.2 shows the contribution of buildings to UK final energy consumption and carbon emissions in 2000. A more detailed breakdown of non-domestic buildings energy consumption in 2000 showed that the education sector accounted for 13 % of the total (DTI, 2002).

The size of the HE estate is increasing year on year, with an increase of 3 % in available space between 2001 and 2003 (HEFCE, 2004). HEIs have a wide variety of buildings used for teaching, research, support and residential purposes. All of these buildings require heating, hot water, electricity, and an increasing proportion requires cooling (**Figure 4.3**).

Table 4.2 The contribution of buildings to UK final energy consumption and carbon emissions
Source: (Sorrell, 2003)

Sector	Final energy use		Carbon emissions	
	PJ	% total	MtC	% total
Commercial and public buildings	880	13.1	21.2	15.1
Industrial buildings	282	4.2	5.6	4.0
Total non-domestic buildings	1162	17.4	26.8	19.0
Domestic buildings	1960	29.3	39.2	27.8
Total buildings	3122	46.6	66.0	46.9
Industrial processes	1231	18.4	27.7	19.7
Transport	2294	34.3	46.0	32.7
Agriculture	49	0.7	1.1	0.8
Total	6696	100.0	140.8	100.0
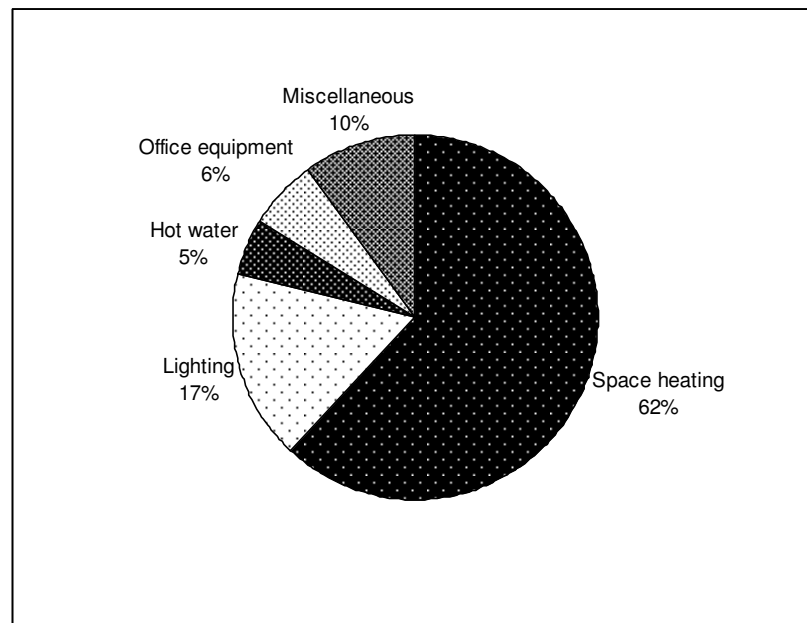
Figure 4.3 HE-Percentage energy use
Source: (Carbon Trust, 2007)

Although there is a wide variety of buildings types in the sector, improving and maintaining

building fabric is a chief energy saving measure. Around two thirds of the energy consumed

in a typical university building is used to replace heat lost through the building fabric (walls,

windows, floors and roofs) (Carbon Trust, 2007). **Figure 4.4** illustrates the percentage of

heat loss from a typical HE building.

The total energy spend in the HE sector is approximately £200million/year, this represents

around 1.8 % of total expenditure by the sector, or 4 % of government spending on HE, and

results in direct and indirect emissions of CO_2 of around 3.2 million tonnes per year (Carbon

Trust, 2007). **Figure 4.5** illustrates the energy use in the HE sector for various building

types. It shows that offices are the largest consumer of energy which accounts for more than

30 % of the total energy use while catering consumes the least energy with 3 % of the total.
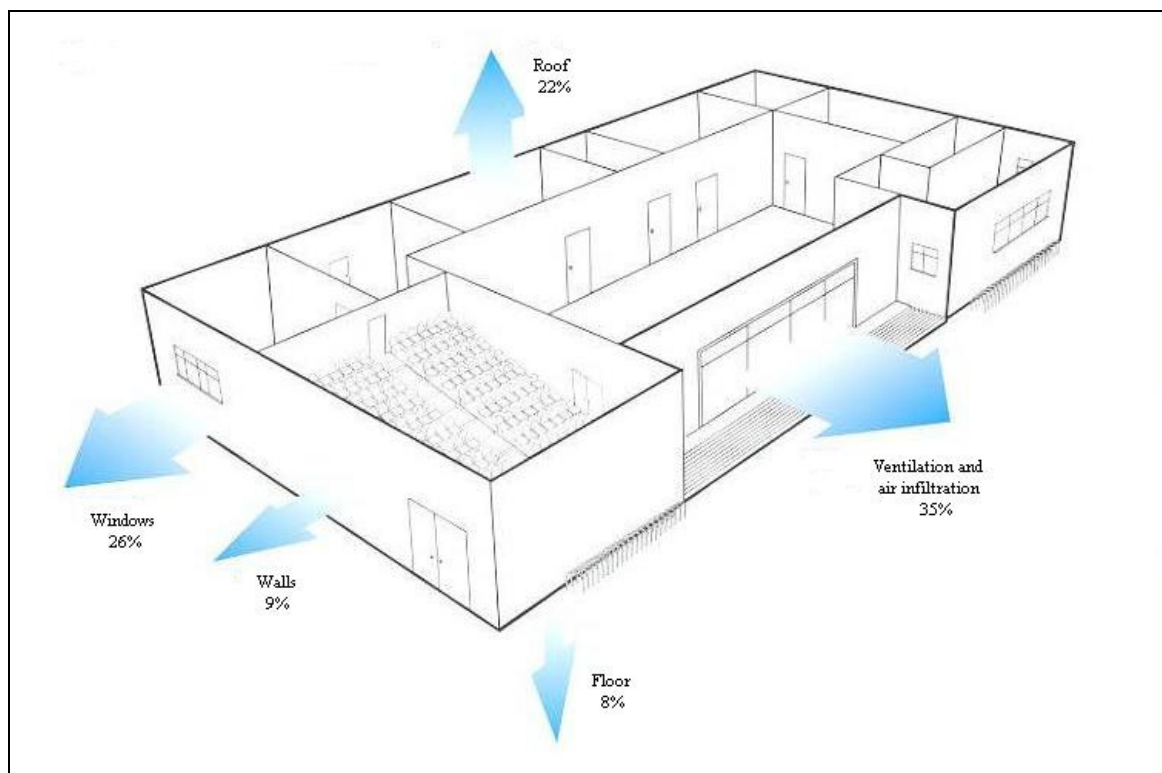
Figure 4.4 Heat loss from a typical HE building
Source: (Carbon Trust, 2007)
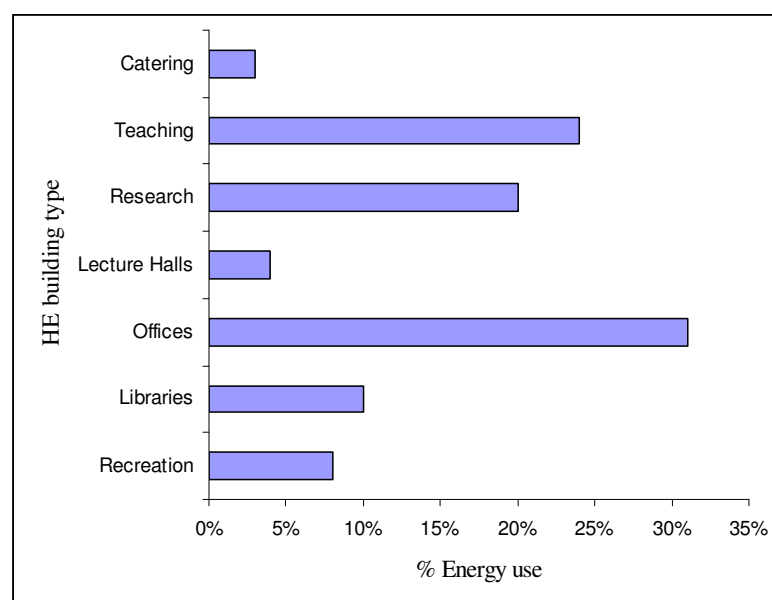
Figure 4.5 Energy use breakdown for HE buildings
Source: (Carbon Trust, 2007).

Clearly, energy performance is a key economic and environmental consideration for HEIs. However, the provision of effective and sustainable refurbishment strategies requires the systematic evaluation of different potential impacts. Any toolkit or framework developed to undertake such evaluation should highlight the key issues that need to be taken into account when identifying the most sustainable refurbishment options and consider the potential impacts of issues associated with each option to ensure a balanced sustainable refurbishment approach.

4.2.4   AUDE Toolkit for Sustainable Refurbishment

To address the issues outlined above (**Section 4.2.3**), AUDE undertook a research project in 2007/2008 which considered the relative sustainability performance of different refurbishment options for the proportion of the HE stock built in the 1960's. The project resulted in a toolkit which can be used to assist HEIs decide whether to refurbish or demolish and rebuild components of this particular segment of the stock. The assessment is based on visual, social, economic and environmental considerations (AUDE, 2008).

The first part of the toolkit is a 'filter' tool that evaluates the potential for refurbishment of an existing building based upon the need to meet an accommodation brief. The purpose of the 'filter' tool is to ensure that the estates team is engaging with the key practicality and sustainability considerations and is clearly guided towards an understanding of the refurbishment potential for the building. The 'filter' tool categories are shown in **Table 4.3**.

Table 4.3 AUDE Tool- Sustainability Considerations
Source: (AUDE, 2008)

Category	Implication
Vision	• Space Accommodation-Evaluation of how well a project brief may be housed • Branding-Suitability of the refurbishment to the university brand or identity • Listing/Heritage-Listed status impacts upon refurbishment options • Masterplan- Integration of refurbishment options with the wider university master plan • Development Restrictions- Planning restrictions impacts upon the refurbishment options
Economic	• Benefit-Financial revenues including rental income, fee income, research income and residual value • Funding Potential-Availability of capital funding for refurbishment options • Risk- Risks arising from uncertainties such as an existing structural condition • Whole Life Costs-Including NPV capital and operational costs • Constructability- Ease of construction and deconstruction • Programme and Phasing- how can the refurbishment be re-commissioned according to shortest programme
Environmental	• Lifecycle- An investigation and evaluation of the environmental impacts of the building over whole life • Environmental Servicing- the ease of implementation of low energy consumption services • Best Practice Environmental Performance- Evaluation of how well the project performance will conform with the current best practice environmental standards • Carbon Emissions- An evaluation of how well the building will perform with relation to carbon emissions • Embodied Environmental Impact- An evaluation of the embodied environmental impacts of different construction materials used in refurbishment • Water Consumption- An evaluation of how well the building will perform in terms of water consumption
Social	• Occupant Comfort Satisfaction- An evaluation of occupant comfort satisfaction • Flexibility- An evaluation of how flexible and adaptable the buildings are to future change of use and education requirements • Good Building Design • Accessibility

The tool comprises a series of questions relating to the university's vision, social, economic and environmental sustainability of the proposed refurbishment. The questions are simply 'yes' or 'no' answers. The tool will steer towards either refurbish or rebuild with a scoring of Low, Medium, High potential for refurbishment. **Figure 4.6** shows the environmental categories of the filter tool.
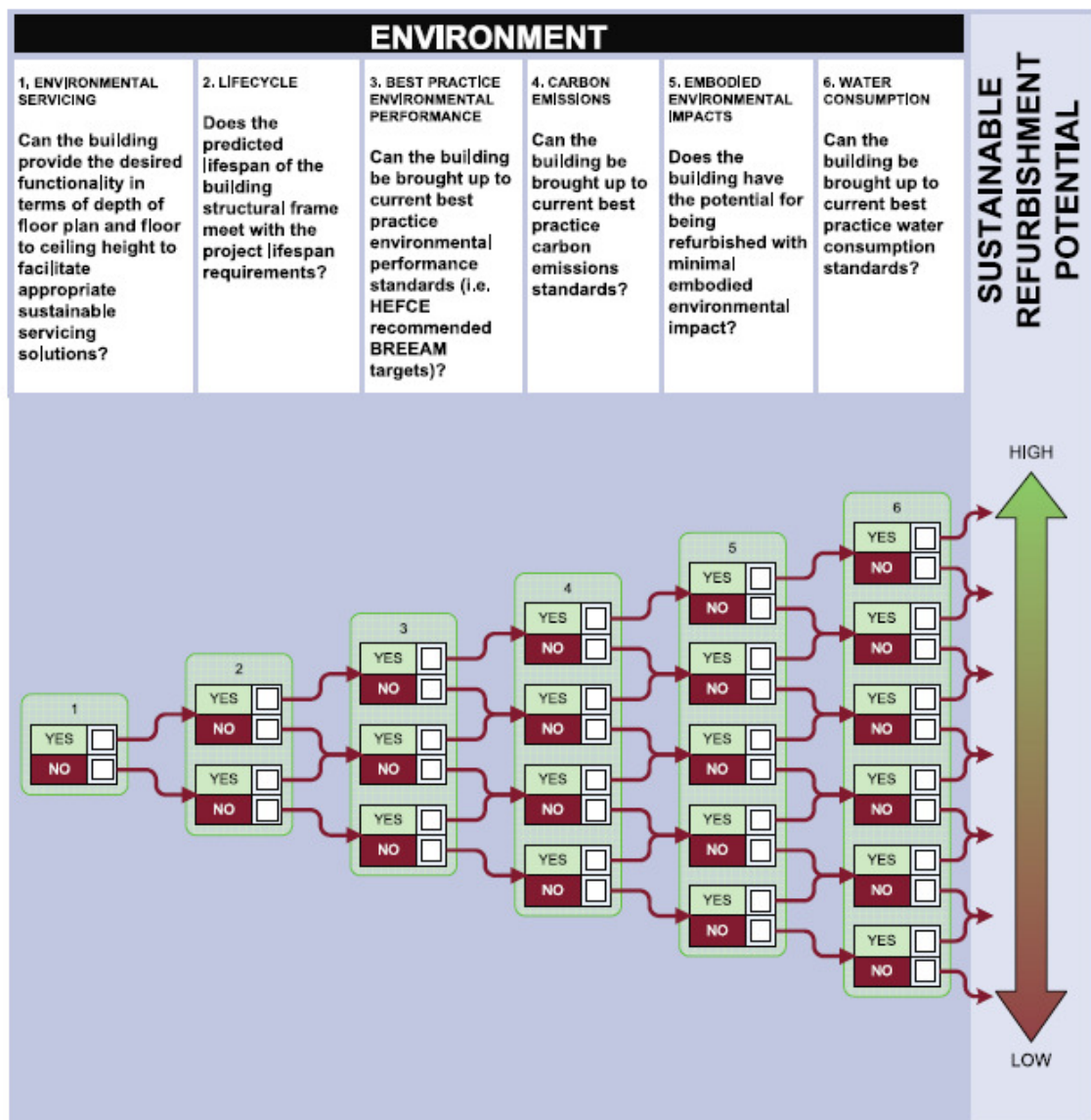
Figure 4.6 Filter tool- Environmental aspect categories
Source: (AUDE, 2008)

It is expected that following the use of the filter tool, the estates team will have been guided towards investigating the feasibility of some different development options that may range from a minimal refurbishment to a full re-build solution.

The second part of the toolkit has been developed as an 'options appraisal matrix' to be used to compare different option proposals for refurbishment based upon the key issues concerning 1960's estate relating to vision, social, economic and environmental sustainability. The purpose of this component of the tool is to promote a balanced approach to sustainability thinking, when considering options for the development of university estates buildings and to allow an accurate reflection of the advantages and disadvantages of each option to be compared (AUDE, 2008).

The options appraisal matrix offers a framework for scoring the sustainability of the different development options using a list of key criteria, some of which are qualitative and some quantitative (**Figure 4.7**). The options appraisal matrix comes complete with guidance notes on how to score against each criterion. The detailed description of the tool and the guidance are available from (AUDE, 2008).

The toolkit represents an essential first step towards addressing the key issues that need to be taken into consideration when identifying the most sustainable refurbishment options for the HE building stock. However, it does not consider the potential impact of uncertainties regarding future climate conditions. Any change in prevailing climate conditions will undoubtedly impact the thermal efficiency within these refurbished estates, and, therefore, the long term sustainability of the building. As a result, any systematic evaluation of a given refurbishment option necessarily needs to consider the impact of future climate change to ensure it is sustainable and effective over its whole life time.

AUDE 1960-70's Buildings						
Matrix Tool Version 1.0						
Jan-08						

Name of Institution:	
Project Title:	
Assessment By:	
Date:	

For each Option, please enter a score between 1 and 5 for each field

Categories	Sub-Categories	OPTION 1	OPTION 2	OPTION 3	OPTION 4	OPTION 5
Vision	Space Accomodation	1	1	1	1	1
	Branding	1	1	1	1	1
	Listing/Heritage	1	1	1	1	1
	Masterplan	1	1	1	1	1
	Development Restrictions	1	1	1	1	1
Social	Occupant Comfort Satisfaction	1	1	1	1	1
	Flexibility	1	1	1	1	1
	Good Building Design	1	1	1	1	1
	Accessibility	1	1	1	1	1
Economic	Whole Life Costs	1	1	1	1	1
	Benefit	1	1	1	1	1
	Risk	1	1	1	1	1
	Funding Potential	1	1	1	1	1
	Legislative Compliance and Asebestos Management	1	1	1	1	1
	De-constructability / Ease of Delivery	1	1	1	1	1
	Programme and Phasing	1	1	1	1	1
Environment	Environmental Servicing	1	1	1	1	1
	Lifecycle	1	1	1	1	1
	Best Practice Environmental Performance	1	1	1	1	1
	Carbon Emissions	1	1	1	1	1
	Embodied Environmental Impact	1	1	1	1	1
	Water Consumption	1	1	1	1	1

Please Note. Embodied environmental impact related issues ('Lifecycle' and 'Embodied Environmental Impact') have an in-built reduced weighting relative to the operational environmental impact related issues. For both refurbishment and new-build projects the average embodied environmental impact is approximated to 25% relative to operational impact over a 30 year lifecycle. See

Category Weightings		OPTION 1	OPTION 2	OPTION 3	OPTION 4	OPTION 5
Vision	25%	5%	5%	5%	5%	5%
Social	25%	5%	5%	5%	5%	5%
Economic	25%	5%	5%	5%	5%	5%
Environment	25%	5%	5%	5%	5%	5%
Overall Score	100%	20%	20%	20%	20%	20%

Figure 4.7 Option appraisal matrix tool
Source: (AUDE, 2008)

4.3   Climate Change Uncertainty and Risk to HEI

As discussed in **Chapter 3**, climate change is one of the greatest challenges facing the world's environment, society and economy today. Its impacts can already be seen across the globe and it poses a threat to every institution in society, including colleges and universities and their host communities (Rappaport and Creighton, 2007). While the fact that the global climate is likely to change over the coming decades is beyond reasonable doubt, the precise nature of that change remains highly uncertain (Shackley et al., 2001; UKCIP, 2008).

The latest projections for climate change in the UK are based on three different scenarios for greenhouse gas emissions: Low, Medium, and High emissions, over seven time slices: 2020s, 2030s, 2040s, 2050s, 2060s, 2070s and 2080s (Jenkins et al., 2009). These scenarios provide a crucial base for research on the impacts of climate change on the built environment and for the identification of appropriate adaptation measures.

Consequently, today's HE building stock and the buildings currently under refurbishment will be operating under different climate conditions in the future and need to be able to respond to climate change (Steemers, 2003). Therefore, the ability of buildings to adapt to changing climate conditions in order to preserve high levels of thermal performance and energy efficiency should play a key role in determining building design or refurbishment strategies.

Traditionally in the UK, most HE buildings rely on opening windows to allow cool outside air to enter and provide thermal comfort in summer. However, as summer temperatures increase - such as those experienced in 2003 and 2006 - the capacity of this traditional

method of cooling will decrease since the outside air is getting warmer leading to increased prevalence of overheating of buildings (Hacker et al., 2005).

Mechanical air conditioning might be seen as an obvious solution to guarantee thermal comfort during hotter summers. However, this solution is undesirable since it will increase the energy demand and compromise greenhouse gas emission reduction targets. Particularly, as cooling is often delivered using electricity with its high CO_2 emissions (CIBSE, 2004). Therefore, there is a need to reduce cooling loads as far as possible using passive and low energy-methods (shading devices, natural ventilation, thermal mass combined with night cooling, and insulation materials) and supply any residual cooling requirements in the most efficient manner.

The goal of refurbishment must be to deliver comfort levels using least energy. But under a changing climate the most efficient solution now might not be suitable and efficient in the future. So there is a need to understand how different refurbishment options function under a variety of plausible future climates to deliver a truly low energy solution over their whole life. This will make HE buildings more comfortable places which consume fewer resources; resulting in enhanced learning environments which boost students' productivity and morale. Moreover, this can reduce operating costs and CO_2 emissions.

Computer simulation is increasingly considered as a useful technique to investigate the thermal behaviour of buildings under changing climate (Clarke, 2001). It enables comprehensive and integrated appraisals of design options under realistic operating conditions to achieve high quality indoor environments.

One aspect of predicting future performance through computer simulation is dealing with uncertainty. This uncertainty arises from different factors, and is associated with uncertainties in the future building itself (e.g. the properties of various building materials, systems might be replaced or upgraded) and operating conditions (e.g. changes in user functions or occupancy pattern), and climate conditions to which the building will be subjected which in turn depends on the future climate change scenario (CIBSE, 1998; Clarke, 2001; de Wit and Augenbroe, 2002).

Such uncertainties could have a considerable impact on the thermal efficiency, and therefore, on the long term environmental and economic performance of buildings, particularly as energy price instability is likely to remain high (IEA, 2009; Gaterell and McEvoy, 2005).

As a result, the next evolution of toolkits and frameworks, such as that developed by AUDE, must include a systematic evaluation of the likely impacts of climate change uncertainty. Without such an approach we cannot ensure any given refurbishment option remains effective and sustainable over its whole life and therefore actually delivers the intended economic and environmental benefits.

4.4   Conclusion

HEIs have a central role in contributing to the agenda for sustainable development, and the significance of the performance of the HEIs estate, which in England comprises approximately 25 million m^2 of gross space, is acknowledged in the development of a strategy for sustainable development in the HE sector.

Most HEIs start adopting sustainable approaches forced by impending legislation, rising energy costs and tightening of building regulations. In general, it is more sustainable to refurbish and re-use existing HE buildings than to demolish and build anew. Refurbishment covers a wide range of activities from relatively minor works to very significant changes to the fabric or internal layout of a building. Considerable sums of money are currently being spent on refurbishing parts of the HEI estate, much of which was built in the post WWII era to thermal standards far lower than those expected today. Clearly, if HEIs are to realise their opportunities to contribute to the sustainable development agenda it is essential that the performance of refurbishment strategies adopted within the estate is evaluated over their whole life.

The development of effective refurbishment options is, in part, dependent on working with the prevailing climate. However, there is increasing evidence that there are likely to be changes to the future climate, although the precise nature of such changes is very uncertain. Given the uncertainty surrounding the long term climatic changes, existing HEIs will need to be flexible enough to adapt to future conditions and be refurbished for, or adaptable to, the climatic conditions expected towards the end of their design life.

The AUDE toolkit represents an essential first step towards addressing the key issues that need to be taken into consideration when identifying the most sustainable refurbishment options for higher education building stock. However, it does not consider the potential impact of uncertainties regarding future climate conditions. Any change in prevailing climate conditions will undoubtedly impact the thermal efficiency within these refurbished estates, and, therefore, the long term sustainability of the building. Assets within a HEI estate have long design lives (80 years or more is not uncommon) and therefore any systematic evaluation of a given refurbishment option such as that developed by AUDE necessarily needs to consider the impact of future climate change to ensure it is sustainable and effective over its whole life time.

CHAPTER FIVE

REFURBISHMENT STRATEGIES

5.1   Introduction

As explained in chapter 4, in the UK there is an increasing tendency towards refurbishing existing HE buildings rather than demolishing and re-building due to the recognition of environmental, economic and social advantages. Many existing naturally ventilated HE buildings now experience overheating problems in summer as a result of climate change (Rappaport and Creighton, 2007). Therefore reducing heat gains and/or providing efficient and low energy cooling systems to maintain internal comfortable conditions should be among the main goals when refurbishing those buildings. This chapter describes two different human thermal comfort theories in buildings and indentifies different passive refurbishment options and strategies that are available and could be applied to the existing HE stock.

5.2   The Need for a Refurbishment Strategy

When refurbishing a building in general the goals are to (Burton, 2001):

- maximise the income or the asset value of the existing building and this is usually the main aim of the building owner;

- adapt the building to comply with new requirements or new use and this is often the main goal of the building user;

- improve the indoor environment and this may be the objective of the occupant; and

- decrease the energy consumption and this goal may be the long term policy of governments and may be enforced by law and building regulations.

While the fact that the last two objectives may at times seem conflicting, a well integrated refurbishment strategy should achieve all these goals at the same time.

To ensure the goals of refurbishment outlined above are achieved, there is a need for an integrated strategy that aims to provide a building which is comfortable with minimised energy requirements. These aims are often achieved by reducing the energy needed for heating, cooling, airflow and artificial lighting, and their associated emissions of CO_2, through a well-designed building (e.g. using passive design measures that take advantage of natural heating, cooling, ventilation and lighting). Any residual demand should be met using efficient and well-controlled mechanical/electrical means.

According to Burton (2001) a well integrated refurbishment design strategy to achieve its goals is likely to include the following steps:

- Understanding the future use of the refurbished building, the occupants' comfort requirements and the surrounding climate conditions;

- Conducting a thorough assessment of the existing building to diagnose the physical and functional state of the building. This assessment should include both a technical survey and an evaluation of occupants' perceptions of the building to reveal problems, weaknesses and opportunities;

- Identifying a wide range of possible low energy refurbishment solutions;

- Carrying out technical analyses using different design tools and considering the interactions between all solutions;

- Choosing the best solution(s); and

- Prioritising chosen solutions according to multi-criteria analysis (e.g. cost, environmental impacts, etc.).

5.3   Occupant Comfort

Providing the optimum internal environment for the occupants is one of the main purposes of the refurbishment. The key physical parameters associated with the internal environmental performance are: thermal comfort, visual comfort, and acoustic comfort (James et al., 2005). However, it is worth noting that general comfort conditions include more qualitative criteria which may be more difficult to satisfy, e.g. local control over conditions, views to the outside, open-plan or cellular layouts. (Baker and Steemers, 2000).

According to Oral et al. (2004) these three physical components are the core aspects for evaluating the performance of a building envelope. These aspects are generally considered in conjunction with aspects of reducing energy consumption for heating in winter and cooling in summer (**Figure 5.1**). By addressing these comfort related aspects during the design phase of a refurbishment project, the need for additional energy requirements to compensate for poor comfort performance will be reduced (James et al., 2005).
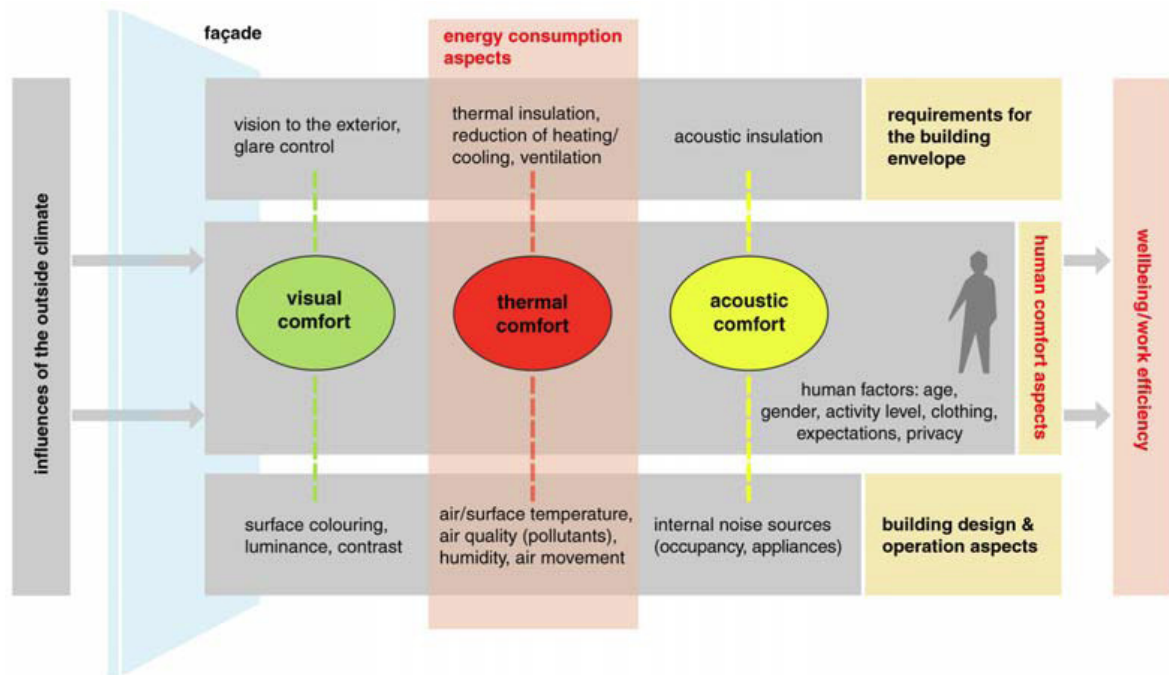
Figure 5.1 Interaction between the human sensation of comfort, building use, building envelope and energy consumption
Source: (James et al., 2005)

Thermal comfort is the most significant factor in the context of climate change and energy conservation. The projected changes in the climatic conditions will have a significant impact on the human thermal comfort and thermal performance of buildings (Nicol and Roaf, 2007; de Wilde et al., 2008).

5.3.1   Thermal Comfort

Different individuals have different perceptions of whether or not a room is 'too hot' or 'too cold' but generally a person is said to be 'comfortable', i.e. neither 'too hot' nor 'too cold' at the so-called neutral temperature (Leaman and Bordass, 2007; Nicol and Humphreys, 2002).

 Thermal comfort is that state of mind that expresses satisfaction with the thermal environment (ASHRAE Standard 55, 2004). Although it is a psychological definition (a state of mind), it has usually been modelled in terms of physiology and physics (Nicol and Roaf, 2007). The interaction between the buildings and their occupants in naturally ventilated

buildings is crucial to the thermal comfort, and therefore, the indoor environment should be designed and controlled effectively so that occupants' comfort is assured.

5.3.2   Adaptive and Deterministic Thermal Comfort Models

Research in human thermal comfort in buildings is generally based on two models namely 'deterministic' model and 'adaptive' model (CIBSE, 2005).

The 'deterministic' model or 'heat balance' model is based on a mathematical formulation of the thermodynamic heat balance of the human body. Peoples' reactions are typically monitored in thermally controlled laboratories over a period of three hours in any one set of thermal conditions (Brager and de Dear, 1998).

The final response of people is usually measured by asking them for a 'comfort vote' on a descriptive scale such as the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) or Bedford scale (**Table 5.1**).

Table 5.1 American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and Bedford scales of user response

ASHRAE descriptor	Numerical equivalent	Bedford descriptor
Hot	3	Much too hot
Warm	2	Too hot
Slightly warm	1	Comfortably warm
Neutral	0	Comfortable
Slightly cool	-1	Comfortably cool
Cool	-2	Too cool
Cold	-3	Much too cool

In order to generalise the results, the responses have been related to a heat balance model-the assumptions being that a pre-condition of thermal neutrality (a 0 response on the ASHRAE scale) will be a (steady state) balance between metabolic heat production and overall heat losses to the environment (Nicol and Roaf, 2007).

Heat balance models consider the occupant as a passive recipient (e.g. no interaction with or adjustment to the surrounding environment) of thermal stimuli and assume that the impacts of a given thermal environment are mediated exclusively by the physics of heat and mass exchanges between body and environment (Brager and de Dear, 1998). Maintaining a constant internal body temperature requires some physiological responses proportional to thermal imbalance.

Thermal sensations [e.g. ASHRAE descriptors in (**Table 5.1**)] are proportional to the magnitude of these responses as measured by mean skin temperature and latent heat loss due to sweating. According to Brager and de Dear (1998) the deterministic logic underpinning the heat balance comfort model is:

physics $---\!\!\!\!\rightarrow$ physiology $---\!\!\!\!\rightarrow$ subjective discomfort

The aim is to find the temperature or combination of thermal variables [temperature, humidity, air velocity, clothing, activity] which people consider 'neutral' or 'comfortable' (Nicol and Humphreys, 2002).

An example of a widely used model of this approach is Fanger model (Fanger, 1970). This model anticipates the predicted mean vote (PMV) or in other words 'the mean thermal sensation' of a large population of people exposed to given environmental conditions (in climate chambers-thermally controlled laboratories) based on the heat balance equations.

This sensation experienced was a function of physiological strain imposed by the environment which Fanger (1970) defined as 'the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort values for skin temperature and sweat production at the actual activity level'.

Fanger (1970) calculated this thermal load for people and used it to predict a comfort vote to that amount of strain, then the predicted percent of dissatisfied people (PPD) at each PMV was determined. As PMV changes away from zero (hotter or colder) in either the positive or negative direction, PPD increases. The Fanger model assumes that thermal sensation is exclusively influenced by four environmental or climatic factors: air temperature, mean-radiant temperature (the mean temperature of all objects surrounding the body), humidity, air speed and two personal factors: clothing level and occupant activity level (Brager and de Dear, 1998).

The final equations for optimal thermal comfort and for PMV are presented in the form of diagrams and tables for a group of people in a particular environment given knowledge of their mean metabolic rate and clothing insulation (Parsons, 2002; Nicol and Roaf, 2007).

The drawback with use of deterministic models, such as the one developed by Fanger, for performance assessment is that they make the same projection for thermal comfort regardless the climatic or social context of the building and its occupants (Hacker and Holmes, 2007). For instance, based on this model, an office worker dressed in a suit in Helsinki would need the same thermal environment as one similarly dressed in New Delhi. Moreover, these models assume that the conditions in the building approach those of the steady state in the climate chamber whereas conditions in buildings are likely to be much more dynamic in terms of both the thermal environment and the occupants' activities.

Both the mean clothing insulation of the buildings' occupants and their mean metabolic rate are difficult to measure which leads to the use of assumptions regarding these variables [e.g. a clothing insulation of 0.5 clo in summer and 1.0 clo in winter; where clo-value is the insulation value of different kinds of clothing 1 clo = 0.155 m^2K/W] (CIBSE, 2006). However, these models are useful due to their high degree of control and reproducibility (Brager and de Dear, 1998).

Conversely, the 'adaptive model', which is empirically based on occupancy comfort surveys of people in buildings worldwide under different climatic conditions, states that factors beyond fundamental physics and physiology play an important role in building occupants' expectations and thermal preferences (Brager and de Dear, 1998; de Dear and Brager, 2002; Nicol and Humphreys, 2002; Hacker and Holmes, 2007).

The fundamental assumption of the adaptive model is expressed by the adaptive principle: if a change causes thermal discomfort, people respond in such a way that their thermal comfort is regained (Hacker and Holmes, 2007). Therefore, under the adaptive model the person is no longer a passive recipient of the given thermal environment but instead is an active agent interacting with the person-environment systems (Brager and de Dear, 1998; Barlow and Fiala, 2007).

According to Brager and de Dear (1998), different forms of adaptation are allowed under the adaptive approach include:

- behavioural adjustments such as opening windows (to change temperature and air movement), clothing adjustments, drawing blinds (to reduce incoming radiation),

adjusting activity levels, changing their location to a more comfortable spot in the room and using desk and ceiling fans but exclude mechanical cooling ;

- physiological adjustments such as genetic adaptation or acclimatisation; and

- psychological adjustments which encompass the effects of cognitive and cultural variables and describe the extent to which expectation and habituation of past thermal history alter one's perception of and reaction to sensory information. For instance, occupants in naturally ventilated buildings have more relaxed expectations and are more tolerant of temperature swings and prefer a wide range of conditions that more closely reflect outdoor climate patterns. In contrast, occupants in closely controlled-air conditioned buildings have much more rigid expectations for a cool, uniformly thermal environment and are more sensitive to changes from these controlled constant conditions (Brager and de Dear, 1998; Nicol and Humphreys, 2002).

Evidence reviewed in Brager and de Dear (1998) indicated that the slower physiological process of acclimatisation appears not to be so relevant to thermal adaptation in the relatively moderate conditions found in buildings, whereas behavioural adjustments and psychological expectations have a much greater influence on thermal comfort.

While the heat balance model can be considered as partially adaptive in the behavioural sense since it accounts for clothing and indoor climatic parameters which can be adjusted by the occupant, it ignores the psychological dimension of adaptation. Psychological adaptation as explained earlier plays an important role in contexts (such as naturally ventilated buildings) where people's interactions with the environment (i.e. personal thermal control) or

diverse thermal experiences may alter their expectations and therefore their personal sensation and satisfaction (de Dear and Brager, 2002).

A widely used adaptive model is Brager and de Dear (de Dear and Brager, 2002). In this model, the indoor comfort temperature required to provide a given level of PPD is provided in terms of mean monthly outdoor air temperature (**Figure 5.2**) (de Dear and Brager, 2002; CISBE, 2005). The mean monthly outdoor air temperature is the ambient dry bulb temperature [called dry bulb because the air temperature indicated by a thermometer is not affected by the moisture of the air, i.e. excluding humidity] (CIBSE, 2005). The indoor comfort temperature, also called the operative room temperature, is the average of air temperature and room surface temperature (CIBSE, 2005).

Figure 5.2 shows that occupants will be comfortable over a wider range of conditions than those predicted by the Fanger model using different adaptive opportunities previously mentioned. Comfort thresholds are shown for discomfort levels of 10 % and 20 % PPD.
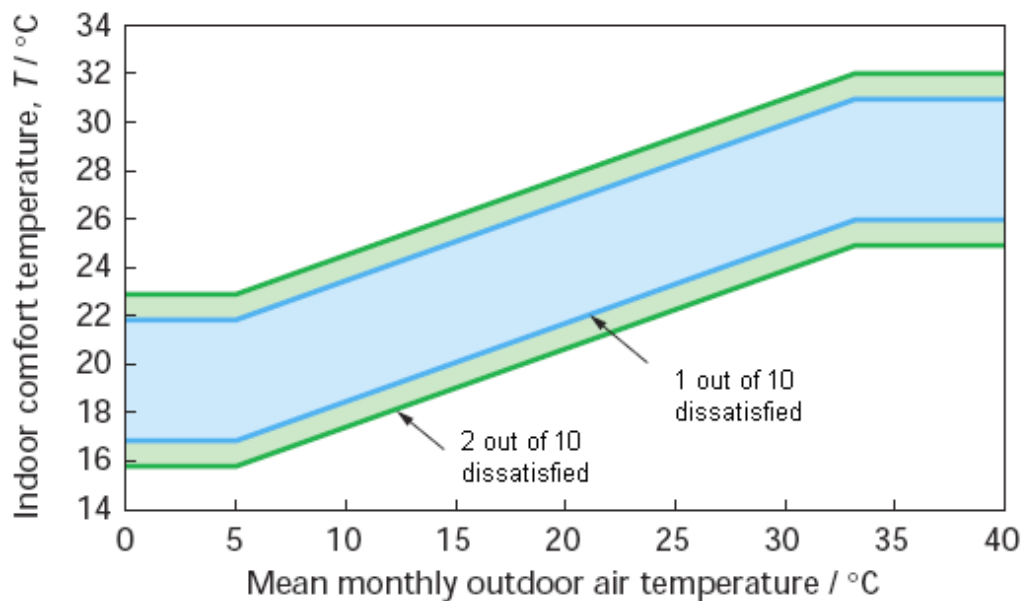
Figure 5.2 Adaptive comfort model (after ASHRAE)
Source: (ASHRAE Standard 55, 2004)

The shaded band of temperatures between the two curves for each level gives the comfort temperature band. For example, if the mean monthly outdoor air temperature is 25°C, 80 % of people will be satisfied at an indoor comfort temperature of between 22°C and 29°C while 90 % of people will be satisfied between 23°C and 28°C. Outside these comfort zones, there will be an increased risk of thermal discomfort (Nicol and Humphreys, 2007).

The adaptive comfort model has found that desired neutral temperatures vary worldwide but correlate with the average outside air temperature. This correlation is thought to be due to psychological part of thermal comfort, particularly adaptation to the local climatic context of the building, which is missing from the Franger model (Hacker and Holmes, 2007).

However, the disadvantage with use of the adaptive model for performance assessment is that the results can be difficult to explain because the benchmarks change from month to month [or day-by-day if a running mean from the previous 30 days is used for the external temperature condition] (CIBSE, 2005). Therefore, a combination of the features of both these modelling approaches will account for both the thermal and non-thermal influences on occupants' response in real buildings.

It is now commonly agreed that the Fanger model provides good projections for PPD in air-conditioned buildings while adaptive models are more suitable for naturally ventilated buildings since the latter is more climatically connected to the outside environment and gives a wider range of adaptive opportunity (Hacker and Holmes, 2007). Several design standards both in Europe and North America have now adopted this principle (de Dear and Brager, 2002; ASHRAE, 2004; van de Linden et al., 2006).

The rationale made for the suitability of adaptive thermal comfort models for naturally ventilated buildings is that the deterministic models are over-conservative in comfort

temperatures and that leads to un-necessary use of air-conditioning (Hacker and Holmes, 2007). For instance, based on deterministic comfort models operative temperatures of 22°C - 24°C are usually specified for air-conditioned offices (CIBSE, 2006).

In the UK, CIBSE has recommended operative temperatures for overheating criteria in naturally ventilated buildings that are broadly consistent with both deterministic and adaptive thermal comfort models. The overheating criteria are that in naturally ventilated buildings the temperature will be acceptable if the inside dry resultant temperature of 28°C is not exceeded for more than 1 % of the annual occupied period, which is typically 20 hours, with the exception of bedrooms in dwellings, for which a lower threshold of 26°C is specified (CIBSE, 2006).

5.4   Passive Building Design

Traditionally, most non-domestic buildings from the 1950s and 1960s had shallow plans with low floor to ceiling height, highly glazed areas and were constructed with lightweight materials and finishes (**Table 5.2**) (Gold and Martin, 1999). These buildings have also experienced increased heat gains from the use of modern IT equipment, more dense occupation, inefficient artificial lighting and increased number of days with high outdoor temperatures [as a consequence of climate change] (Burton, 2001). The combination of thermally poor building design and increased heat gains have resulted in more overheated conditions in these buildings, unless mechanical cooling is provided (CIBSE, 2005).

However, the reliance on mechanical equipment to provide acceptable internal comfort conditions incurs capital and operating costs and contributes to carbon emissions to the atmosphere.

Table 5.2 Characteristic of different building types
Source: (Gold and Martin, 1999)

Period	Advantages	Disadvantages
1900- pre WW II	High ceilings Designed for natural ventilation. Narrow floor plate aids this. Possibility to add solar shading and spot cooling in high heat gain areas. Heating, power and communications routed around perimeter.	May be listed building (delays due to negotiation with English Heritage). Structural partitions- inflexible space, poor circulation, poor insulation. Low floor loading (may not accommodate current loads without strengthening)
Late 1950s/1960s	Open plan layout Designed for natural ventilation. Narrow floor plate aids this. Possibility to add solar shading and spot cooling in high heat gain areas. Heating, power and communications routed around perimeter.	May be listed building Low floor-floor height Large glazed areas leading to high heat gain. Low floor loading (may not accommodate current loads without strengthening) Relatively lightweight structure. Poor insulation and high air infiltration rates. Single glazing Addition of raised floor complicated around lifts and stairwells. Routing ducts and pipe work may be difficult.
1970s	Open-plan layout Larger floor-floor height than 1960s (for services)	May be listed building Deep plan, need for air conditioning and artificial lighting Lightweight construction. Possible high air infiltration through façade Poor insulation High heat gain through fully glazed façade
1980s-1990s	Larger floor-floor height. Raised floor for services. Open and deep plan layout. High electrical power capacity	Lightweight construction. Over-specified ventilation and air conditioning- difficult to control

An alternative approach is to take the outdoor climate and comfort criteria into consideration when refurbishing buildings and to try to adapt them to the surrounding climate. In the present context 'passive or low-energy design' is, as previously defined in chapter 2 (section 2.9), the process of reducing the need for mechanical heating, cooling, lighting and ventilation while maintaining an acceptable internal environment by utilising solar energy, natural ventilation and using the fabric of the buildings (e.g. walls, windows, shade, etc.) (Holmes and Hacker, 2007).

Clearly, the building envelope which acts as a mediator between the inside and outside environment plays a vital role in this approach. Mechanical systems could be installed to offset any remaining mismatches between free-running (i.e. not heated or cooled) and required comfort conditions. Following this passive approach is likely to significantly reduce the energy consumption and generally give better internal comfort conditions (Burton, 2001).

5.5   Building Design Issues

A combination of natural flows of heat associated with external climate and indoor heat gains determine the temperature of a room in any given building (Hacker et al., 2005; Watts and Thomas, 2006). Optimising these heat flows to make the best use of the external climate is the principal aim of the passive design.

According to Hacker et al. (2005) the main aspects of the design of a building are divided into both climate and non-climate associated design issues (**Figure 5.3**).

1. Insulation.
2. Glazing.
3. Ventilation.
4. Air-tightness.
5. Thermal mass.
6. Internal gains.
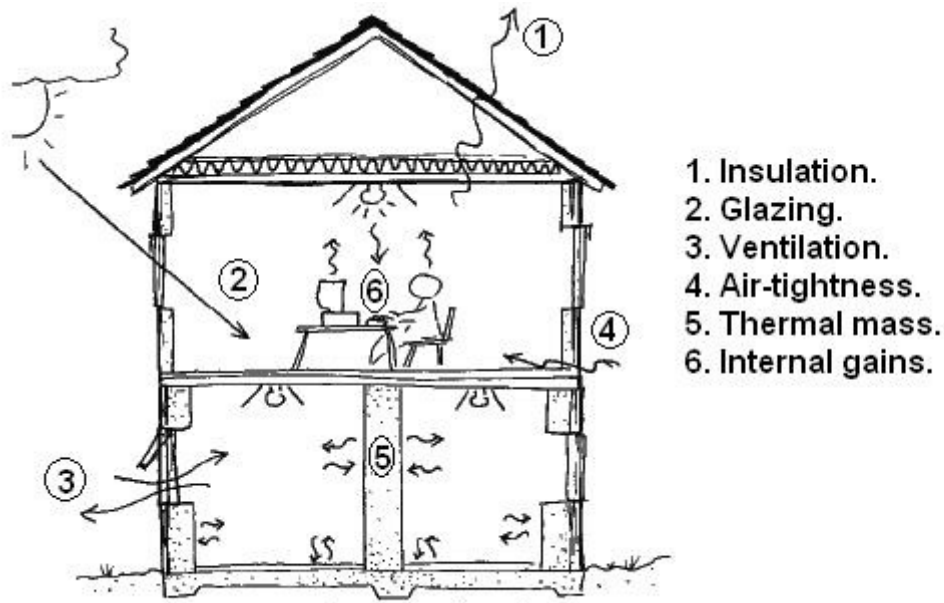
Figure 5.3 Climatic and non-climatic design issues
Source: (Hacker et al., 2005)

5.5.1 Climatic design issues: The most important climate variables affecting the indoor climate are sunshine, temperature, humidity and wind speed. The following are the main climatic design issues and the associated climate factors are shown in brackets:

a. Insulation (temperature and sunshine): In winter, insulation reduces heat loss from buildings by trapping heat inside while in summer it could have two impacts: a useful one of stopping heat entering the building during the day and an undesirable one of stopping heat flowing out at night.

b. Glazing (sunshine): Light passes through glass into the room, warms up surfaces and produces radiant heat. Then the glass traps this heat since it is an effective absorber of infrared radiation. Therefore, un-shaded windows are considered as a major source of heat build-up in buildings.

c. Ventilation (temperature, humidity and wind speed): Ventilation is essential to health and well being by maintaining the indoor air quality. It also comprises one of the largest heat flows. In winter, with the aim of reducing the need to heat cold air coming in from outside, ventilation is usually kept to minimum. While in summer, ventilation is considered as a source of cooling. This is only the case when the outside air is cooler than the inside air of the building; otherwise, ventilation becomes a heating source.

However, studies have shown that the air movement generated by open windows can provide cooling even at higher temperatures by helping people to sweat, with a maximum desirable speed of 0.8 m/s giving about 3°C of perceived cooling (Rennie and Parand, 1998). Ventilation also plays a key role in determining the indoor humidity (Hacker et al., 2005). High relative humidity could reduce the ability of body to lose heat through perspiration and cause thermal discomfort and heat stress.

Natural driving forces for ventilation are provided by wind speed and buoyancy flow (stack effect) due to temperature differences (Rennie and Parand, 1998). Wind speed increases with height above the ground level. Wind generates pressure differences across the building which cause air to flow through openings in the building envelop.

'Buoyancy flow' or is more commonly known as 'stack effect' [because it is the force which powers the chimney stack] results from the difference in air temperature between indoor and outdoor (Rennie and Parand, 1998). The warm air is lighter than the cold air surrounding it which therefore replaces it.

The size of the stack effect depends on the temperature difference between internal and external air and also on the height of the column of internal air (**Figure 5.4**) (Rennie and Parand, 1998; Littlefair et al., 2000). As shown in **Figure 5.4a** the stack effect is greater if the temperature difference is greater. Also, the stack effect is greater in the taller building as there is a greater head of cold air (**Figure 5.4b**) (Rennie and Parand, 1998).

d. Air tightness (temperature and wind speed): Infiltration is the process of exchanging the air between the building and the external environment through small cracks and draughts in the building envelope (Roaf et al., 2008). This process is controlled by improving construction quality.

(a) Temperature difference between indoor and outdoor	(b) Building height
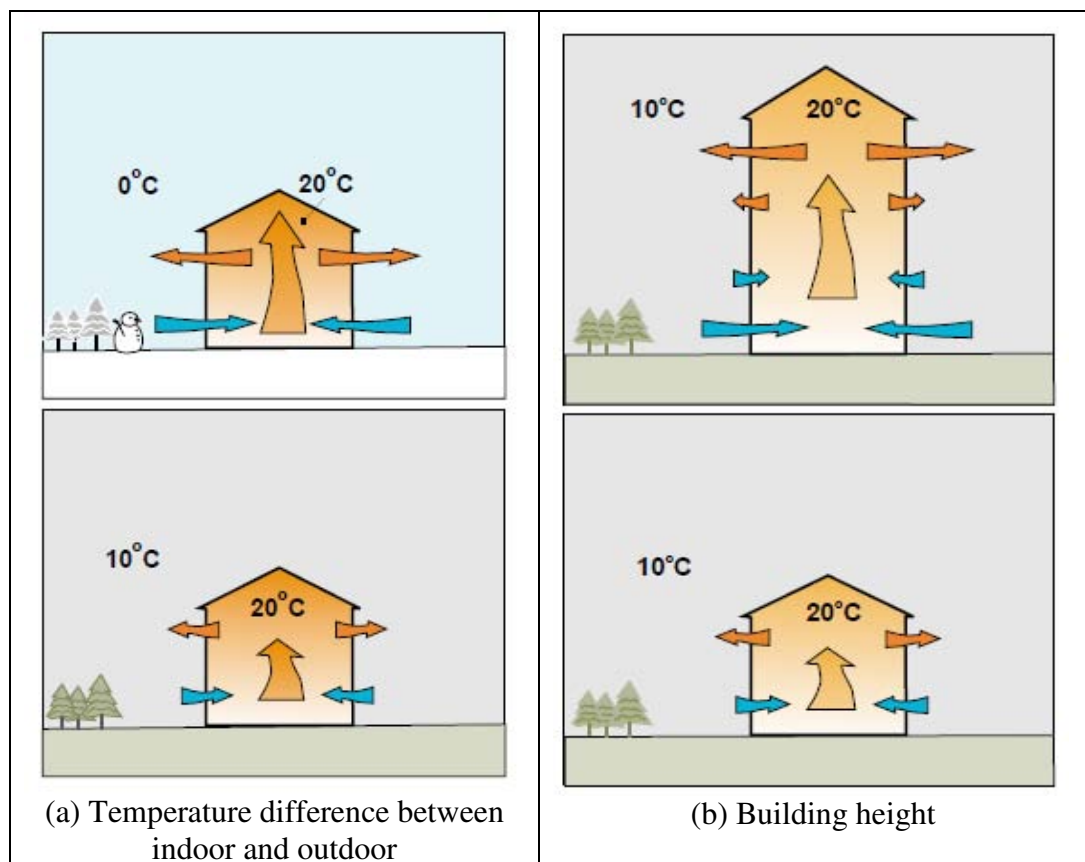
Figure 5.4 The stack effect
Source: (Rennie and Parand, 1998)

- Thermal mass (temperature): It is the element of the building such as concrete or brick which has the ability to store and release a considerable amount of heat during a typical daily cycle (Upadhay, 2008). It reduces swings in the indoor daily temperatures compared to the outside temperature variation. A room with high thermal mass would heat up much more slowly than low thermal mass because more heat is absorbed by the mass (McMullan, 2007).

  However, it has a potentially undesirable effect of keeping a building warmer at night. Therefore, to ensure effectiveness in summer, heat absorbed during the day needs to be managed by combining thermal mass with night cooling.

5.5.2 Non-climatic design issues

a. Internal gains: Buildings have considerable internal heat inputs from occupants, computers, lighting and other electrical equipment.

b. Heating systems: Gas-fired central heating is the typical heating system in the majority of UK buildings (Hacker et al., 2005). With well insulated fabric and proper air tightness, trapped internal gains can considerably reduce the demand on the heating system.

c. Cooling systems: Ventilation and thermal mass are normally considered as the natural sources of cooling in buildings. However, these sources are not guaranteed to provide cooling for the building all over the year particularly in warmer climate conditions (Baker, 2009). Therefore, some buildings might require mechanical cooling such as air-conditioning systems or other less energy intensive options (e.g. chilled beam and slab).

5.6   Passive Refurbishment Options

Low energy adaptation options which allow occupants to create their own thermal preferences by interacting with their environment, modifying their behaviour or gradually adapting their expectations to match the surrounding thermal conditions are essential to improve existing buildings capacities to maintain comfort levels (Brager and de Dear, 1998; Barlow and Fiala, 2007).

Two levels of adaptive opportunities can be considered when refurbishing HE buildings, i.e. active [where building occupants interfere to change their thermal environment using active measures e.g. mechanical equipment] and passive [where a building's environment or fabric is adapted without active occupant intervention]. Both active and passive adaptive opportunities are important in future low energy HE refurbishment strategies (Barlow and Fiala, 2007).

The aim of energy efficient refurbishment design is to minimise the energy required, by active measures, and their associated CO_2 emissions by utilising natural forces (e.g. solar energy and natural ventilation) and improving the thermal properties of the building's fabric (Burton, 2001). For this reason, this research focuses on passive refurbishment options to improve the energy efficiency of HE buildings and provide required indoor thermal comfort. Any further energy demand required after that to meet comfort conditions should be supplied using the most efficient and well-controlled mechanical equipment. Applying strategic refurbishment decisions to reduce heat gain at source by adopting passive design solutions will have a knock-on effect on the actual performance of building over its life time and on occupants' satisfaction.

These passive solutions are likely to include:

1. upgrading the building fabric by increasing insulation levels or replacing windows with more efficient one to reduce gains and improve the thermal performance of the building;

2. reducing the unwanted solar gain by introducing shading devices;

3. reducing internal gains from lighting and equipment as much as possible by the use of energy efficient lighting and equipment;

4. using natural ventilation to remove excess heat when the external temperatures are lower than the internal ones; and

5. using thermal mass coupled with night ventilation to lower daytime temperatures.

The first three measures can be considered as passive measures to reduce heat gains while the last two measures can be considered as passive cooling measures.

5.6.1   Passive Measures to Reduce Heat Gains

(a) Insulation

Insulation of walls, floors and roofs can be placed either on the outside or the inside of the existing structure or within the cavity (Burton, 2001). Insulation on the cold side of the building or '*external insulation*' is preferred as it reduces thermal bridging [i.e. junction points where insulation is not continuous and results in heat loss] (Szokolay, 2008). External insulation also maintains a more stable structure temperature by reducing fluctuations in air temperature, ensures that any condensation occurs outside, and keeps internal thermal mass

high allowing night ventilation cooling and a heat sink to even out temperature swings. Therefore, it is favoured in case of summer cooling strategies.

Conversely, insulation on the warm side of a building or '*internal insulation*' often results in thermal bridges, a risk of interstitial condensation (i.e. condensation within the structural elements) and reduced internal thermal mass and room size. However, internal insulation is sometimes preferred in the case of heating the building and in refurbishment because it may be easier and cheaper to install and does not change the appearance of the building (Burton, 2001).

'Cavity insulation' has no effect on internal or outside appearance or on room size and can be applied without disturbing the occupants. It permits the warm side of the building to function as a thermal mass and substantially reduces the risk of condensation within the building. It also reduces the problems from thermal bridges (Gorse and Highfield, 2009).

A disadvantage with insulation in general is that it can prevent the building from cooling down at night (Hacker et al., 2005). In practice, several types of organic and inorganic insulations can be found (**Table 5.3**).

Table 5.3 Insulating materials
Source: (Krope and Goricanec, 2009)

Inorganic materials		Natural or organic materials	
Mineral fibres	**Foam materials**	**Plants and animal fibres**	**Foam materials**
Slag wool	Expanded glass	Cellulose fibres	Polyester foam
Glass wool	Vermiculite	Wool	Phenolic foam
Rock wool	Perlite	Straw	Extruded polyester
	Expanded clay	Cotton	Polystyrene foam
		Paper	Polyurethane foam
		Cork	

Debate on the choice of insulation materials tends to be related to environmental considerations, buildability and thermal efficiency (Thomas, 2006). Regarding the environmental aspects and in particular the embodied energy, insulation materials derived from mineral fibres tend to require less embodied energy than a number of others (**Table 5.4**); similarly they have lower CO_2 emissions.

Turning to buildability, expanded polystyrene (EPS) foams are preferred because of the ability to lap boards and maintain a clear cavity. Additionally, they have good water resistance and are economically and environmentally friendly (Thomas, 2006).

Table 5.4 Properties of common insulating materials
Source: (Thomas, 2006)

Material	Thermal Conductivity (W/mK)	Density (kg/m^3)	Thermal resistance (mK/W)	Embodied energy (kWh/m^3)
Expanded Polystyrene (EPS) foam board	0.035	25	28.6	1126
Mineral wool quilt	0.040	12	25.0	231
Mineral wool slab	0.035	25	28.6	231
Phenolic foam board	0.020	30	50.0	1126
Polyurethane board	0.025	30	40.0	1126
Cellulose fibre	0.035	25	28.6	133
Wool	0.037	16	27.0	31

The thermal efficiency of an insulant is denoted by its thermal conductivity (λ) and is measured in W/mK. The thermal conductivity is 'the property of a material indicating its ability to conduct heat' (Smith, 2005). Technically, it is a measure of the rate of heat conduction through $1m^3$ of a material with a $1°C$ temperature difference across the two opposite faces. The lower the value, the more efficient the material used as an insulator (Smith, 2005).

Conductivity is a material property, regardless of its shape or size (Szokolay, 2008). The thermal resistance (R) is a measure of a material's thermal performance taking into account the material's thickness. The thermal resistance is calculated by dividing the material's thickness (t), in metres by its thermal conductivity (λ) and is measured in m^2K/W (**Eqn 5.1**).

$$R = \frac{t}{\lambda}$$
Eqn 5.1

Table 5.4 shows the thermal conductivity, density, thermal resistance, and embodied energy of common insulating materials. The thermal transmittance, which is more commonly known as U-value, indicates the rate of heat flow through a complete element of a building, e.g. a wall, floor or window. It is the reciprocal of the sum of thermal resistances of the components that make up the building element and is measured in W/m^2K (**Eqn 5.2**) (CIBSE, 2006). A lower U-value means a greater resistance and better performance.

$$U = \frac{1}{\Sigma R}$$
Eqn 5.2

The U-value is used to calculate the heat loss or gain (Q) through the building fabric by multiplying the U-value of the element in W/m^2K by its area (A) in m^2 and by the difference in temperature (ΔT) in K between the outside (T_o) and inside air (T_i) and is measured in W

(**Eqn 5.3**) (CIBSE, 2006). If ΔT is taken as $(T_o - T_i)$ then a negative value, thus also a negative Q, will indicate heat loss, whilst a positive value would mean heat gain.

$$Q = U \times A \times \Delta T \hspace{4cm} \text{Eqn 5.3}$$

Thermal insulation as a refurbishment option plays an important role in reducing the U-value for the wall, floors and roof sections and therefore reducing the heat loss and maintaining internal surfaces at higher temperature than would otherwise be the case, thus improving comfort levels.

(b) Windows

Windows are the most energy-transmissive elements in the building envelope (Baker, 2009). Although glazing can admit useful solar energy that can limit the reliance on artificial lighting, one of the main energy consumers in HE buildings, it is considered a poor insulator (Baker and Steemers, 2000). Even the highest performance glazing has a U-value at least five times greater than typical insulated opaque elements (Baker, 2009). As the area of glazing is increased to collect more energy, the potential for heat losses through glazing is also increased.

According to Baker (2009) optical and thermal transmittance are the key characteristics of glazing. The performance of glazing in admitting visible daylight and keeping heat in, or, in an over-heated climate, keeping heat out, is determined by the values of these two parameters. Since the thermal performance of different refurbishment options is investigated in this study, only thermal transmittance of glazing is considered.

Heat losses through glazing usually comprise a large part of the total heat loss in existing HE buildings and account for 26 % of the total heat loss through building fabric (Carbon Trust, 2007), since old windows have relatively poor thermal properties. This is often the case both for the glazing itself and for the frames (Baker, 2009).

Heat is lost to the internal glass surface from the room whenever the glass surface is at a lower temperature than the internal air temperature and the room surface temperature.

The heat is lost through a glass unit in three ways (Button and Pye, 1993) (**Figure 5.5**):

- by long wave radiation exchange between the glass surface and the room surfaces

- by convection/conduction from the room air moving over the surface of the glass and a conduction losses through the frame components

- by air flow through the window both designed (ventilation) and unintentional (infiltration).
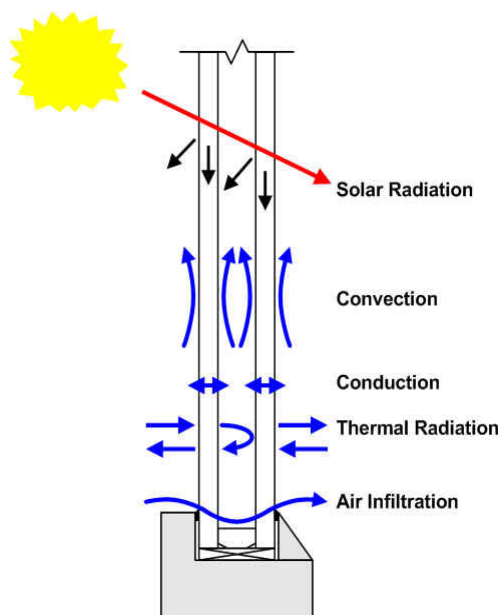
Figure 5.5 Heat loss through glazing
Source: (Carbon Trust, 2007)

The thermal performance of single glazing can be improved by (Muneer et al., 2000):

- Increasing the resistance to loss of heat by adding two or three panes separated by an air space to form an additional resistive layer rather than one. The surfaces of the glass present a resistance to the convective component which reduces the U-value. However, there is a limit due to convection within the air space, which occurs at about 15 mm after which little thermal benefit is obtained.

- Incorporating low emissivity coatings to the surface of the inner side that faces the cavity. This very thin metallic layer transmits short wavelengths (i.e. visible light) but operates as a poor emitter for long-wave infrared. In double-glazed windows for instance, if the inner side of the glass surface that faces the cavity has a coating with emissivity less than 0.2 (compared with 0.88 for the uncoated glass surface), the radiation exchange is decreased by approximately 75 % and consequently the U-value is decreased (Muneer et al., 2000).

- Using gases of lower conductivity such as Argon and Krypton within the gap between panes. This will reduce the convective transfer further and result in lower U-value.

Table 5.5 shows indicative U-values for both glazing and frame of typical windows used for conceptual design. It is worth noting that the use of such improved glazing may result in reduced daylighting and solar energy collection. However, the heat gain/loss ratio will be enormously improved (Muneer et al., 2000). Windows frames should either be made from insulating materials, such as wood or should include thermal breaks to reduce heat loss (Burton, 2001).

Table 5.5 Indicative U-values for windows for conceptual design[*].
Source: (McMullan, 2007)

Item	U-value of glazing + framing (W/m^2 K)
Single glazing, metal frames	5.7
Single glazing, wood or PVC frames	4.8
Double glazing, wood or PVC frames, low emissivity, 6mm gap with inert gas	2.7
Triple glazing, wood or PVC frames, low emissivity, 12 mm gap with inert gas	1.6

[*] The full procedure for calculating the whole window U-values can be found in (CIBSE, 2006)

(c) Solar Shading

Shading decreases solar heat entering the room via windows and causing overheating in summer, while some direct solar gains may be beneficial in winter. Other aspects of shading are to reduce glare and thus improve the visual comfort in the working spaces and to provide privacy for the occupants (Littlefair, 1999).

Currently, the need for shading is widely recognised. In the post-war period, there was a trend for large areas of glazing and lightweight construction as energy consumption was not the main driver. If problems of overheating occurred in summer, these could be managed by the use of air-conditioning systems (Baker, 2009).

Vernacular architecture [a term applied to local buildings that have developed over time in one location to suit the local climate, culture and economy] with its rich traditions of louvres, shutters, overhangs and blinds clearly revealed that before this wasteful period, the use of passive low-energy design could avoid need for artificial cooling (Nicol and Roaf, 2007). If climate change is taken into account, the gradual shift from the problem of heating to that of

cooling can be addressed through the use of shading. Therefore, the understanding and the adoption of shading have now become an essential part of sustainable refurbishment. **Figure 5.6** shows some examples of different solar shading systems

Figure 5.6 Examples of solar shading systems: (a) Overhang (b) External louvre (c) Tinted glazing (d) Window film (e) Venetian blind (f) Roller blind
Source: (Szokolay, 2008)

Solar shading techniques can be divided into four main categories:

> *External Shading*

External shading devices can be classified as fixed or movable: fixed horizontal overhangs and louvres, vertical side fins, movable horizontal or vertical louvres, and vertical roller shades (Burton, 2001).

All fixed devices limit the amount of sunlight entering the place at particular time of the year when natural light would be most welcome and usually they only provide partial shading. In the UK, they are rarely used on east and west elevations due to low Sun angles (**Figure 5.7a**), but can be more effective on the south elevation, allowing low winter Sun in but excluding high summer Sun (**Figure 5.7b**) when overheating is most likely (Baker, 2009). Conversely, movable devices are more flexible to provide shading only when it is wanted since they can be adjusted either manually or automatically.
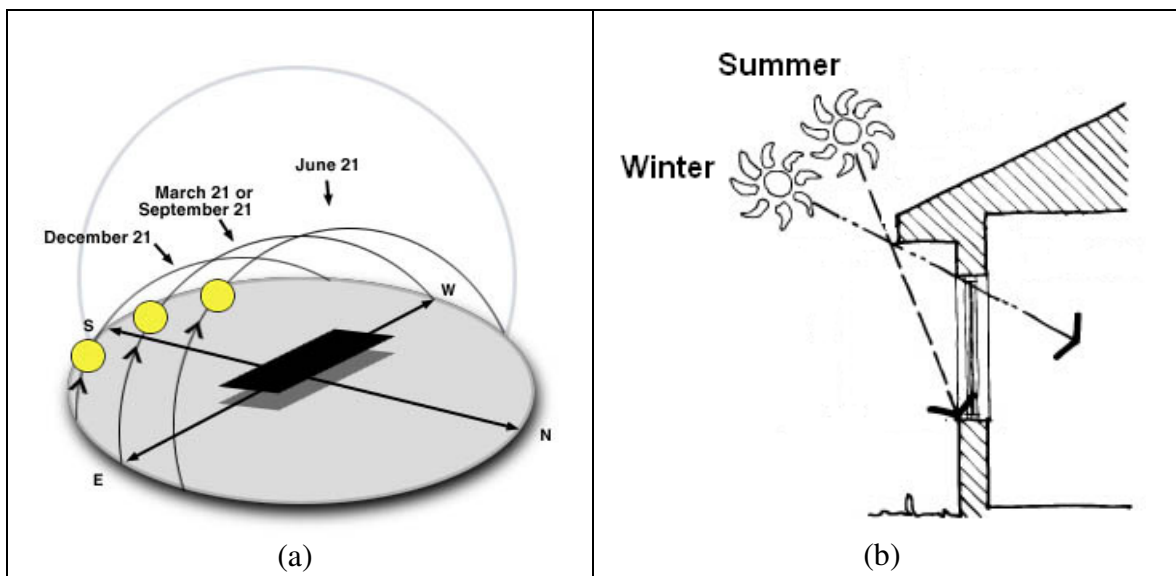
Figure 5.7 (a) Sun path in the UK (b) Impact of external shading on the south elevation in summer and winter
Source: (Szokolay, 2008)

➢ *Interpane Shading*

Interpane shading usually includes adjustable (remains in position but radiation transmission can be modulated e.g. changing angle of louvre) and retractable (can be removed completely from the aperture) venetian or roller blinds, or films which are held between two panes of a multi-glazed unit (**Figure 5.8**) (Baker, 2009). The advantage of using this type of shading is that it is protected from weather, dust and mechanical damage so little maintenance and cleaning are required. However, they are expensive and can only be used with a complete window replacement (Kendrick et al., 1998).

Figure 5.8 Interpane shading
Source: (Okalux, 2010)

➢ *Internal Shading*

Generally, venetian or roller blinds are used for internal shading. This shading system offers occupants local control with easy and low cost installation, accessibility and requires low maintenance. However, it is not an effective method of excluding solar heat gain as heat is

trapped inside the building after hitting the shade. Operation can also interfere with window opening and air flow (Burton, 2001).

> *Solar Control Glass (Glazing)*

Solar control glass can be either body-tinted (**Figure 5.6c**) [glass coloured by incorporation of a mineral admixture] to absorb solar radiation or coated with a reflective layer (Baker, 2009). However, the use of tinted and reflective glass is not recommended as a shading strategy since it reduces the daylight thus increasing the use of artificial lighting and excluding potentially useful solar gains in winter (Baker and Steemers, 2000).

The type of shading used will depend upon the nature of refurbishment, the orientation of the façade, the glazed area, the budget and any other restrictions such as planning constraints relating to the building (Baker, 2009). According to Kendrick et al. (1998), glazed areas below 20 % of wall area require no shading; glazed areas of 20 % to 50 % can use internal shading, and anything above 50 % may need external shading to keep internal conditions comfortable in summer.

The method of comparing the performance of different windows or shading systems is by using the total solar transmittance. The total solar transmittance is the fraction of the incoming solar radiation that passes through a window and/or shading system and is often called as the 'g-value' (Littlefair, 2005). The total solar transmittance includes both radiation that is transmitted directly through the window and/ or the shading system, and radiation that is absorbed and then re-radiated, convected or conducted to the room. (Littlefair, 2005).

However, some manufacturers use shading coefficient (SC). This figure is the ratio of the total solar radiant heat transmittance with the device in place to that of an unprotected single sheet of 4 mm clear float glass (taken as 0.87) (Kendrick, 1998). For example, a double glazed unit with 6 mm clear float glass either side of a 12 mm air space has a total solar radiant heat transmittance of 0.72, and hence has a shading coefficient of 0.72/0.87 = 0.83.

Table 5.6 summarises the performance data for the different shading systems. The transmittances are all relative to those for clear double glazing. It should be noted that the solar transmittances will vary for different examples of the same system. Also it will vary for different window orientations (Littlefair, 2002).

From (**Table 5.6)**, it can be seen that external louvre systems are the most effective way of controlling solar gain. However, internal shading systems (curtains, venetian blind and roller blind) provide greater adjustability compared with external shading systems (overhang and external louvre) and can be applied on different orientations.

Table 5.6 Summary of performance data for different shading systems
Source: (Littlefair, 2002)

Shading system		Best for window types	Relative total solar transmittance (south facing)		Adjustability
			Summer	Winter	
Clear double glazing, no shading		—	1	1	X
Overhang		S	0.55	0.84	☺
External louvre:	Shut Open	HSEW HSEW	0.04 0.26	0.04 0.45	☺ *
Tinted glazing		SEWH	0.71	0.68	X
Window film		SEWH	0.51	0.49	X
Mid-pane Venetian:	Shut Open	NSEW NSEW	0.43 —	0.43 —	☺☺ *
Fixed mid-pane louvres		H	0.37	0.90	☺
Curtains		Any	0.50	0.49	☺☺☺
Venetian blind:	Shut Open	Any	0.57 —	0.58 —	☺☺☺
Roller blind		Any	0.43	0.43	☺☺☺

Key to the table

Window types	N = North, S = South, E = East, W = West, H = Horizontal
Adjustability	X = performance does not vary significantly (no user control, no variation with season), ☺ = seasonal variation in performance, ☺☺ = some user adjustability, ☺☺☺ = completely adjustable, * = some types completely adjustable

(d) Reducing internal gains from lighting and equipment

As previously shown in (**Figure 4.3**) page 79, electricity for lighting is a major use of energy and source of heat gains in the HE buildings. This may be largely due to the adoption of unnecessarily high lighting levels or inefficient lighting systems. Additionally, the growth of business machines and IT has led to a significant increase in heat gain produced in HE buildings (Baker and Steemers, 2000).

Both lighting and equipment heat gains may be partially beneficial in winter to offset heating loads; however, they contribute to overheating in summer. Any refurbishment strategy should aim to reduce lighting energy use by optimising daylight and using energy efficient lighting systems. For office equipment, the effect of internal gains can be reduced by incorporating low energy equipment (e.g. photocopiers with low power stand-by mode) and placing them where possible in areas of high ventilation away from occupants or in separate rooms (Baker and Steemers, 2000).

5.6.2   Passive cooling using natural ventilation and thermal mass

(a) Natural Ventilation

Natural ventilation is the most obvious measure to provide natural cooling (Baker and Steemers, 2000). Many HE buildings are naturally ventilated and if this can be maintained with adequate indoor air quality after refurbishment, a low energy and comfortable solution should result. If the outdoor air temperature is lower than or equal to the designed indoor temperature (18°C-24°C), ventilation can be used as a means to remove excessive heat gains from the indoor spaces to the atmosphere.

However, in hot conditions and where the ambient temperature is above the upper limit of comfort, ventilation will cause heat gain and it should be reduced to the minimum needed for fresh air requirement. In this situation the only alternative to mechanical cooling is to rely on any 'coolth' which was stored efficiently in the fabric overnight when the external air was much cooler than the building (Rennie and Parand, 1998).

(b) Thermal mass

Thermal mass, as defined earlier, is the material of the building which has the ability to absorb and release heat from or to the interior space (Baker and Steemers, 2000). Incorporating thermal mass in buildings helps to balance fluctuating temperatures across the diurnal cycle (Upadhay, 2008). Heat storage within the building structure acts as a temporary heat sink offering a means for the control of indoor temperature variations throughout the day (Baker, 2009).

The admittance (Y-value) is used to compare the thermal mass of different building materials. The admittance of the material is the rate at which a square metre of its surface can absorb heat from the air for a temperature difference of 1°C and measured in W/m^2K (Rennie and Parand, 1998). The admittance of the material depends on its thickness, conductivity, density and specific heat (Thomas and Fordham, 2006).

The admittance of some common wall constructions is shown in (**Figure 5.9**). The thermal mass of whole rooms can also be calculated by summing the energy admittances of each of the room's surfaces and dividing this by its floor area. **Table 5.7** shows the thermal mass of some typical office rooms.
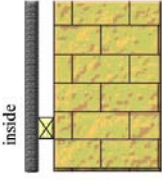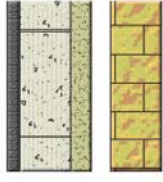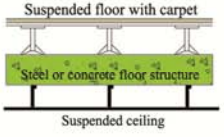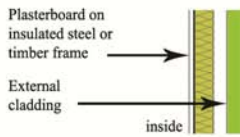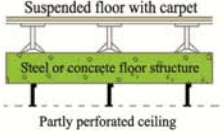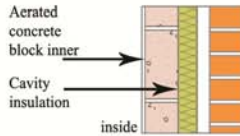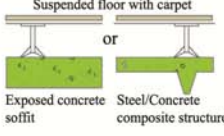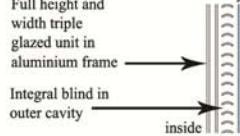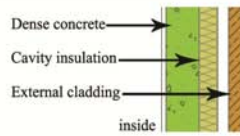
Figure 5.9 Admittance (Y-value) of some common wall constructions (W/m^{2}K)
Source: (Rennie and Parand, 1998)

Table 5.7 The thermal mass of some typical office rooms
Source: (Rennie and Parand, 1998)

The greater the admittance value, the smaller the temperature swing inside the building (McMullan, 2007). Dense heavyweight materials such as concrete tend to have larger admittance values than less dense lightweight materials such as wood and thermal insulating materials. Consequently, thermally heavyweight structures have smaller and slower temperature swings than thermally lightweight structures (**Figure 5.10**) (Braham et al., 2001).

While the unit for admittance value is the same as for U-value, it is possible to have elements of different construction with identical U-values but different admittance values. **Table 5.8** illustrates one example.
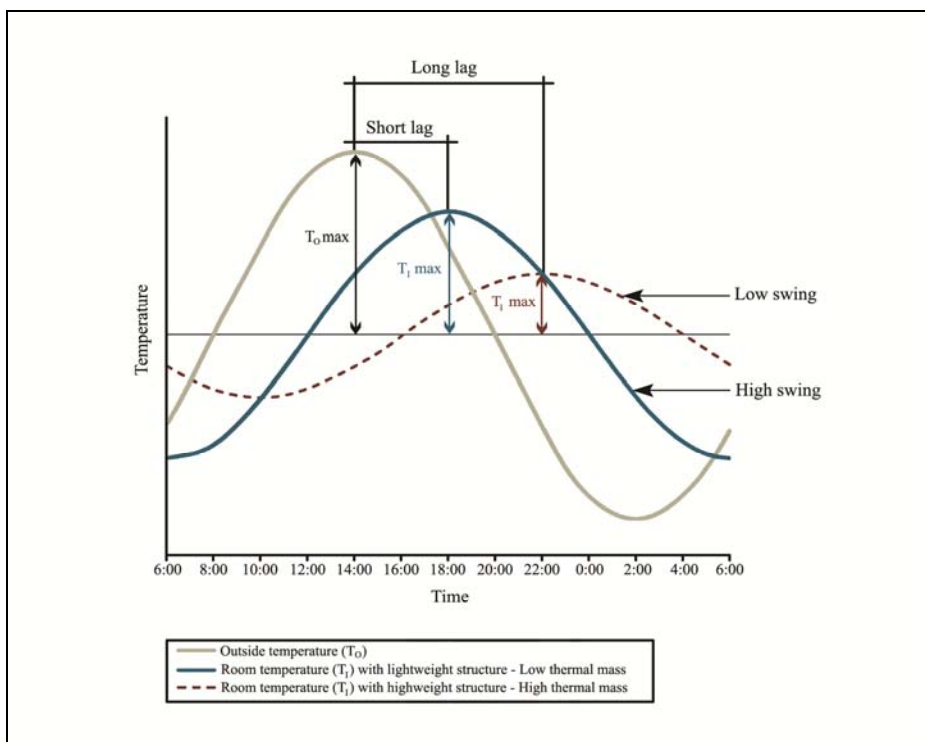
Figure 5.10 Thermal response
Source: (McMullan, 2007)

Table 5.8 Contrasting values of transmittance (U-value) and admittance (Y-value)
Source: (CIBSE, 2006)

Element	U-value (W/m^{2}K)	Y-value (W/m^{2}K)
Solid wall (220 mm solid brick, 50 mm mineral wool insulation, 12.5 mm plasterboard)	0.63	0.89
Cavity wall (105 mm brick, 50 mm EPS insulation, 100 mm dense concrete block, 13 mm dense plaster)	0.63	5.57

According to Gold and Martin (1999) most post-war non-domestic buildings, including HE, have a thermally lightweight structure, lightweight carpeted floors and lightweight suspended ceilings for IT cables, pipes, wires and other services. These buildings characteristics limit the usefulness and the effectiveness of the thermal mass. Increasing the thermal mass of these thermally lightweight structures as a refurbishment solution is not practicable (e.g. loss of useful space, not cost effective). For thermal mass cooling techniques to be efficient, there must be a low cost means of dissipating heat during the night. The usual method is to open windows at night, but there are disadvantages in the HE sector (security issues, rain ingress, insects etc.). For these reasons, the use of increased thermal mass has not been considered as a refurbishment solution in this work.

5.7   Conclusion

In the context of climate change, while the aims of refurbishment include maintaining indoor thermal comfort and reducing energy consumption, the need to adopt an integrated strategy to achieve these goals is of paramount importance. This integrated strategy should include addressing the issues of eliminating or reducing additional solar heat gains built up in buildings as a result of a warming climate and if necessary providing cooling using low energy measures.

Although the conventional response of installing air-conditioning into existing HE buildings to maintain comfort conditions may be seen as an obvious solution to overheating problems, this solution is likely to result in increasing levels of energy use and CO_2 emissions.

Thermal comfort research has concluded that people are generally thermally comfortable below 28°C in the UK provided that they are able to adapt actively their activity, clothing levels and passively to their local environment to improve comfort conditions. Integrating passive adaptive measures into the refurbishment cycles could increase their resilience to the effects of climate change, while helping to prevent an increase in energy use and CO_2 emissions associated with installing air-conditioning systems.

Different passive measures are available including improving the thermal performance of the fabric through the use of insulation materials, glazing technologies and shading devices, and providing natural cooling using natural ventilation and thermal mass.

However, questions remain as how these options will function under different climate change scenarios and which of these options are more likely to remain effective in the face of future climate change projections. The aim of this work is to provide an analysis of

modelling these options for future climate projections. This will help to provide refurbished

buildings that are more flexible and able to perform effectively over a range of future climate

conditions and efficiently at low energy consumption rates.

CHAPTER SIX

MUIRHEAD TOWER CASE STUDY BUILDING

6.1   Introduction

To investigate the likely impacts of climate change on thermal comfort levels in existing HE buildings in the UK and the viability of passive adaptation options under the current set of future climate change scenarios for the UK, a case study building has been developed. The analyses are based on dynamic thermal model (DTM) computer simulations, which replicate the physical reality of the building, with the model being driven by weather data adjusted for climate change.

Several studies have been undertaken in Europe using this method to investigate the impact of climate change on thermal comfort and energy use in buildings. Cullen (2001) used warm UK weather data to model a conventional office building under naturally ventilated and air conditioned-scenarios. Aguiar et al. (2002) investigated the changes in the heating and cooling energy demand in both air-conditioned domestic and service sector buildings in Portugal under climate change scenarios for the 2080 timeslice (the period from 2071 to 2100). Results from their work suggested that energy demand for space conditioning in Portugal would increase by the end of the twenty-first century. Although the heating energy demand will be reduced as climate change progresses, the extended cooling season and large increases in cooling energy will offset these savings in heating energy demand. Aguiar et al.

(2002) highlight the need for better understanding of climate change and its impacts and the modification of building characteristics to deal with these changes accordingly.

Frank (2005) investigated the potential effects of climate change on heating and cooling energy consumption in domestic and commercial buildings for Switzerland using historical data from warm years as an analogue of future climate change. Results from this study show a 33-44 % decrease in the annual heating demand while the annual cooling energy demand will increase by 223-1050 % for the period of 2050-2100 as a result of climate change. The study also concluded that efficient solar shading and night ventilation strategies are capable of keeping indoor air temperatures within an acceptable comfort range and reducing the need for cooling equipment are set to become a crucial building design issue.

Gaterell and McEvoy (2005) investigated the impact of different insulation measures, applied to an existing residential dwelling, on heating and cooling loads using weather data for Italy as an analogue for future UK climate. However, it should be noted that taking Italy's weather data as an analogue for future UK climate is not a useful practical and realistic assumption. Temperature is only one facet of climate affecting thermal comfort in buildings as discussed in **Chapter 5** (**Section 5.5**). One of the other important factors is the sunshine (Hacker et al., 2005). The level and intensity of the sunshine in the absence of cloud cover is determined by latitude (Kibert, 2008) and therefore will always be greater in Italy than the UK.

A collaborative research undertaken by Arup, CIBSE and UKCIP has examined different residential, educational (schools) and commercial case study buildings using DTM simulations under the UKCIP02 scenarios (CIBSE, 2005; Hacker et al., 2005). The analysis was made for three case study locations (London, Manchester and Edinburgh) and three

timeslices (2020s, 2050s and 2080s), investigating both existing performance and passive and mechanical adaptation measures (Hacker and Holmes, 2007). The results of this research suggest that applying low-energy design measures offers the best 'future proof' solutions.

However, none of these studies outlined above have quantified the likely impacts of future climate change scenarios on the HE buildings, or have explored in detail the performance of different refurbishment options available for passive cooling. This chapter aims to address these issues.

6.2   Summary of the Methodology

Step 1: Case Study Identification

Muirhead Tower at the University of Birmingham was selected as a case study building. This building represents a typical of many HE buildings built in the UK in the post-war era (**Section 6.4**).

↓

Step 2: Data Preparation

a) As-built drawings for Muihead Tower were studied and information related to the Tower such as building plan and sections, notes on material and use were gathered (**Section 6.4**).

b) A geometric model of three representative rooms within the Tower was constructed in detail (cellular office, open-plan office and teaching room) and examined under different orientations i.e. North, South, East and West (**Section 6.4).**

c) Databases for constructions, glazing types, internal gain sources and profiles, occupancy patterns, ventilation, airtightness and heating systems (**Table 6.1**).

↓

Step 3: Simulation and Analysis

a) IES thermal simulation programme was used. Three applications of IES were used which are MoelIT, SunCast and ApacheSim (**Section 6.3**).

b) Birmingham TRY and DSY weather files both under the present-day climate conditions and under future climate change scenarios were used for thermal modelling (**Section 6.5**).

c) CIBSE guidance for thermal comfort criteria in naturally ventilated building was followed (**Section 6.6**).

d) CO_2 emissions have been calculated based on an assumed mix of fuel types following UK Building Regulations 2006 (**Section 6.7**).

e) CIBSE energy consumption benchmarks for the three rooms were used to validate the simulation results (**Section 6.8**).

f) Seven different refurbishment options were identified and examined under present-day climate condition and different climate change scenarios (**Section 6.9).**

↓

Step 4: Reporting

Results for the number of hours above the comfort level, energy consumption of the heating and cooling systems and the associated CO2 emissions for each refurbishment option under the present-day and for different climate change scenarios were presented (**Section 6.10**).

6.3   IES Thermal Simulation Tool

Real scale experimentation and computer simulation are two approaches currently used to predict the thermal performance of buildings because they can integrate their complex physical processes (Burton, 2001). Since the experimental approach is time consuming and expensive, computer simulation is generally used (Citherlet et al., 2001).

Computer simulation facilitates the assessment of the response of a building (as-designed, as built and as-operated facilities) or building component to specified external conditions using a computer model (de Wit, 2004). Additionally, computer simulation can not only predict the end result but also identify the physical processes that have led to that result (CIBSE, 1998).

Computer simulation speeds up the design process, increases efficiency and enables the comparison of a broader range of design options. Computer simulation also provides a better understanding of the consequences of design decisions (Augenbroe, 2004). Therefore, it is used as a tool to answer 'what if' type questions (de Wit, 2004). 'What would happen if we would make this design alteration?'What would be the effect of this type of refurbishment?' 'How would the building respond to these extreme conditions?' This type of questions typically arises in a decision-making context, where the consequences of various alternative courses of action are to be assessed (de Wit, 2004).

In the UK, thermal building performance can be predicted using many building energy simulation programmes include, amongst others, ESP-r, Energy Plus, DesignBuilder, Hevacomp, Tas Building Designer and Integrated Environmental Solutions (IES) (Tzempelikos and Athienitis, 2007; Jentsch et al., 2008). These building simulation programmes model the energy flows in buildings and between buildings and their local

environment to predict their likely performance and aid the choice of design solutions (Pilgrim et al., 2003; de Wilde and Augenbroe, 2009).

By facilitating the careful consideration of different design options, these building simulation programmes can help designers ensure that good internal conditions can be achieved under all foreseeable operating conditions. Moreover, they can assist in reducing both energy consumption and the extent of mechanical cooling, so minimising the likelihood of greenhouse gases being emitted (CIBSE, 1998).

A good overview of building energy software tools is the directory provided by the US Department of Energy (2010). This directory now lists more than 300 tools, ranging from software that is still under development to commercially available software.

IES simulation programme was used in this study (**Figure 6.1**). IES is an integrated collection of applications linked by a common user interface i.e. where people (users) interact with the software to manipulate inputs or outputs and a single integrated data model (Muhaisen and Gadi, 2006). This means that the data input for one application can be used by the others, which allows simulation of different aspects of building performance (e.g. thermal, lighting, air flow and mechanical simulation) within the same programme (IES, 2010). IES provides detailed evaluation of building and system designs, allowing them to be optimised with regard to comfort criteria and energy use (Crawley et al., 2005).
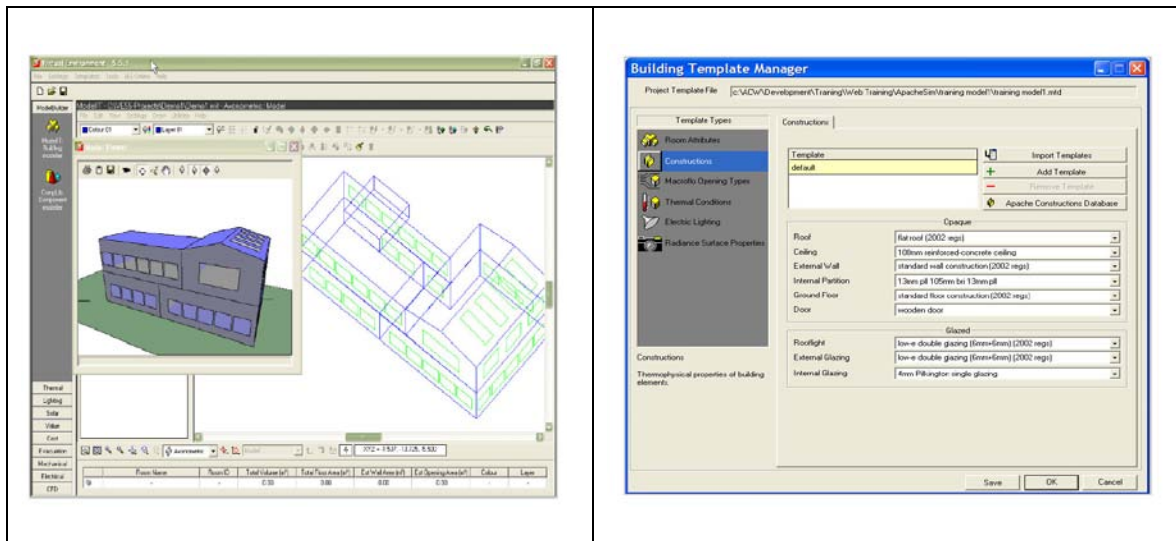
Figure 6.1 IES Software
Source: (IES, 2010)

IES has been assessed under international validation test (ASHRAE Standard 140) and found

to give predictions close to the median of predictions of other DTMs (IES, 2001). Moreover,

IES has been approved for use in compliance checking according to the 2006 part L2 of the

Building Regulations for England and Wales (ODPM, 2006). A good in-depth description of

the IES simulation programme, its applications and capabilities, can be found in IES (2010).

Within IES, heat transfer processes by conduction [i.e. within a body or bodies in contact],

convection [i.e. from a solid body to a fluid (liquid or gas) or vice versa] and radiation [i.e.

from a body with a warmer surface to another which is cooler] for each element of the

building fabric are individually modelled and integrated with models of room internal heat

gains and air exchanges (IES, 2010).

IES consists of different applications, each one performs specific calculations. 'ModelIT' is

used for generating a building model (rooms shape, size etc.), 'ApacheSim' for thermal

simulation analysis, 'Radiance' for lighting simulation analysis, 'ApacheHVAC' for

component based system simulation and 'SunCast' for detailed shading and solar penetration

analysis (IES, 2010). This study investigates the thermal performance of different suggested refurbishment options and therefore, only three applications of IES were used to carry out the investigation, which are ModelIT, SunCast and ApacheSim.

Among the issues that can be addressed within these three applications are: thermal insulation (type and placement), building configuration and orientation, climate response, glazing, shading, solar and internal gains (IES, 2010). The simulation is determined using real weather data and can cover any period from a day to a year.

Simulation results are viewed in Vista, a graphics driven tool for data presentation and analysis (IES, 2010). Vista provides facilities for interrogating the results in detail and includes functions for statistical analysis (Crawley et al., 2005). Simulation results include:

- Over 40 measures of room performance including air and radiant temperature, humidity, solar gain and internal gains;

- Comfort statistics;

- Heating and cooling energy consumption;

- CO_2 emissions.

6.4   Muirhead Tower Case Study Building

Muirhead Tower (**Figure 6.2**) at the University of Birmingham in the UK was constructed in 1974 (Associated Architects, 2007). This tower is typical of many HE buildings built in the UK in the 1960s and 1970s. The building comprises 2, 12-storey towers linked by a central core with 2 below-ground floors, accommodating 150 academic offices, 230 postgraduate

write up spaces and 7 teaching rooms. Each block is approximately 32m x12m in plan (**Figure 6.3**).

North elevation
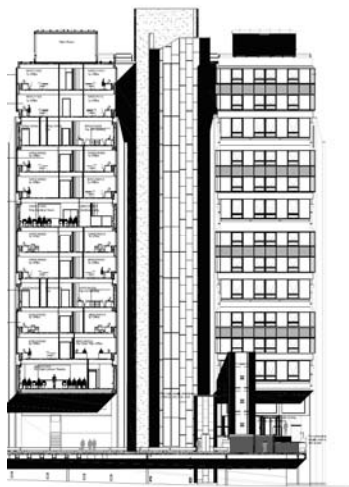
West elevation

     North elevation   **West elevation**

Figure 6.2 Muirhead Tower: North and West elevation
Source: (Robinson, 2005)

Tower blocks are considered as the most vulnerable building type to climate change due to their high exposure to the climate elements and their unfavourable volume to surface ratio (Bahaj et al., 2008).

Cellular offices floor   Open plan research offices floor   Teaching rooms floor
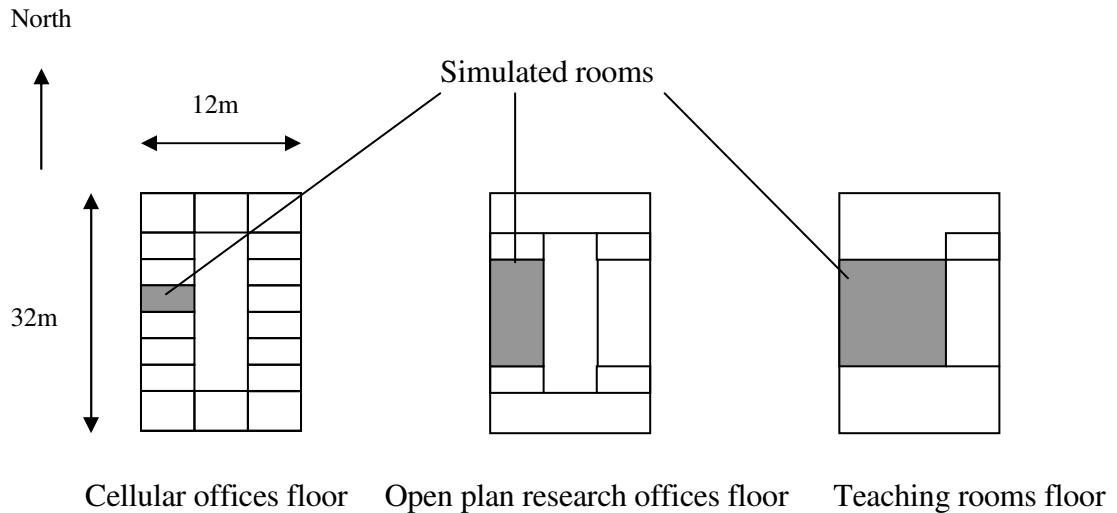
Figure 6.3 Typical floor plans of Muirhead Tower

Muirhead Tower is considered an appropriate case study building to be investigated under current and future climate change scenarios for various reasons:

- It represents a typical higher educational building which was built in the post-war era.
- It has a rectangle plan of 32m x 12m covering 12 storeys, and therefore high volume to surface ratio.
- It is naturally ventilated.
- Its envelope is poorly insulated with high glazing ratios and poor airtightness.
- Its façade is unshaded by other buildings.
- It comprises a mixture of cellular, open plan offices and lecture rooms.
- It has high occupancy and equipment density on the majority of floors.

The building is to be refurbished with a clear policy not to install air conditioning if it is possible. An acceptable thermal performance in summer time has to be achieved by passive means if it is possible under current and future climate change conditions. Therefore, careful planning in terms of façade properties, window type, solar control and internal gains is required.

Due to the repetitive nature of the blocks, it was decided to construct a geometric model of three representative floors in detail rather than to build a model of the whole building (**Figure 6.3**). This would allow extrapolation to the whole building and permit more detailed studies of specific issues at a later design stage. Three rooms (cellular office, open plan research office and teaching room) were selected for detailed analysis and examined under different orientations (**Figure 6.4**).

This selection was based upon (**Figure 4.5**) page 80 which shows that these kinds of rooms are likely to be the most energy intensive in a typical HE building. A free horizon and no external shading were assumed for the building as built. Each room essentially represents a separate thermal zone in the simulation model (i.e. ceiling, floor, internal walls were modelled as adiabatic-no heat transfer) to prevent any heat gain or loss from other rooms except from the façade in question (CIBSE, 1998). This would allow the performance of different refurbishment options applied to the façade in question to be compared directly.

Occupancy and internal loads have been modelled according to the on site surveys of electrical equipment and typical daily occupancy patterns. This may cause strong differences between potential and actual occupancy density during working hours as simulation assumptions and real occupancy patterns may not always match (e.g. some students may be absent in some days).

Cellular office   Open plan office   Teaching room
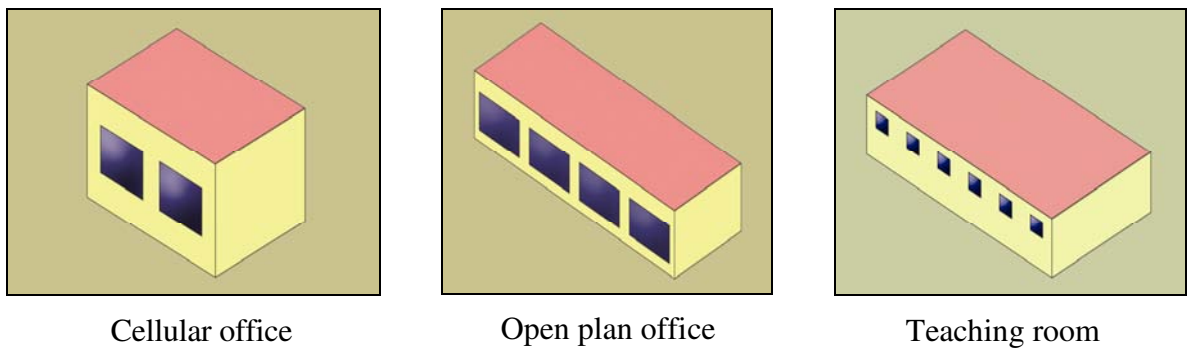
Figure 6.4 Perspective views of the rooms as modelled in the IES simulation programme

In addition, human behaviour patterns such as window opening may vary significantly from prior assumptions depending on the individual users. Combined with uncertainties within thermal simulation programme itself this may result in significant variance between thermal comfort predictions and reality (Macdonald and Strachan, 2001). However, since relative performance will be compared, the results and the decisions made upon them will not be affected.

The simulation parameters for these rooms are given in **Table 6.1**. They have been derived from on-site surveys, selected literature values (CIBSE, 2006) and from meetings with estate managers at the University of Birmingham. To provide a consistent base for comparisons, these parameters will be used for all simulation runs, regardless of potential future changes to occupancy profiles and thermal loads of office equipment and building services (lighting).

Table 6.1 Muirhead Tower: Thermal simulation parameters for the three selected rooms

Room	Cellular office	Open-plan research office	Teaching room
Base parameters			
Floor area/room height	17.5m^2/ 3.2m	75m^2/3.6m	120m^2/3.6
Glazing to wall ratio	44%	55%	10%
Occupancy	1 person (80 W)	15 people (1200 W)	100 people (8000 W)
Construction parameters			
External walls	10.5 cm concrete panel, 1.3cm mineral wool, 10 cm lightweight concrete blocks, 1.3 cm plaster, U-value = 1.5W/m^2.K		
Glazing	*Glazing*: 4mm single glazing: U-value = 5.30 W/m^2.K, g-value =0.85, *Frame*: steel, 20% of window area, U-value = 5.00 W/m^2.K		
Internal walls	Office separation walls: 2.5cm plasterboard, 4cm mineral wool, 2.5 cm plasterboard Corridor walls: 1.3 cm plaster, 10cm light weight concrete blocks, 1.3 cm plaster		
Floor	7.5 cm reinforced concrete slab, 2.5cm screed, 5mm PVC tiles.		
Internal gains			
People	Activity level: occupants seated, light work Weekdays: 08:00-17:00	Activity level: occupants seated, light work Weekdays: 08:00-17:00	Activity level: occupants seated, light work Weekdays: 09:00-17:00
Equipment	1 PC (140 W) 1 inkjet printer (15 W)	15 PC (2100 W) 1 inkjet printer (15 W)	1 PC (140 W) 1 projector (250 W)
Artificial lighting	12 W/m^2 fluorescent tubes with electronic ballast, direct lighting modelled to be switched on within the working time on weekdays.		
Heating	Set temperature 20°C from 7:00-18:00 and 14°C from 18:00-7:00, off during the summer months (June-September inclusive).		
Ventilation	Natural ventilation provided by openable window only, assumed that the windows are able to provide up to a fixed maximum ventilation rate of 6 air changes per hour (ACH).		
Airtightness	Background infiltration of 1 ACH.		
Cooling	No active cooling system.		

6.5   Using Weather Data and Climate Change Scenarios

6.5.1   Weather Data

When an existing building is to be refurbished, the local climate of the site is taken into account by the design team to adapt the building to this climate to provide an amenable and comfortable interior (Burton, 2001). Building simulation programmes, as discussed in (**Section 6.3**), are becoming increasingly important for assessing and predicting building performance in terms of energy and comfort (Citherlet et al., 2001; Clarke, 2001). This assessment involves constructing a computer model. The model is typically used to predict performance over a complete year of weather data, which is called 'weather year'.

Historically, designers have used observed weather records to provide a clear perception of potential weather conditions that their buildings might experience in the future (Levermore and Parkinson, 2006). The average characteristics of climate were thought to be noticeably unchanging over time and the longer the period of observed weather records, the better predictions of future conditions. However, under changing climate the assumption that the climate is stationary is not true (Hacker et al., 2009).

Current industry standard weather files used for building simulation are not appropriate to assess the potential impacts of a changing climate particularly summer overheating risks (Jentsch et al., 2008). Although these weather data files can be used to predict performance under 'present-day' climate condition therefore, the need for suitable climate change weather files for building performance assessment is pressing. Even under current climatic conditions, increasing proportions of the building stock in the UK, in particular naturally

ventilated buildings often perform poorly during periods of hot weather (Jentsch et al., 2008).

In the UK, CIBSE has produced two different simulation weather file sets, Test Reference Year (TRY) files for Heating, Ventilation and Air Conditioning (HVAC) planning and Design Summer Year (DSY) files for assessing summertime overheating risks (CIBSE, 2002; Levermore and Parkinson, 2006). These files were initially covered three UK sites: London, Manchester and Edinburgh. However, since 2006 files are available for 14 sites throughout the UK (Levermore and Parkinson, 2006). The current CIBSE TRY and DSY files are derived from measured UK Meteorological (Met) Office site data from 1983 to 2004.

TRY is considered as a 'typical year' for calculation of average annual energy consumption by simulation under typical weather conditions (Hacker et al., 2009). The definition of typicality is based on a combination of three weather variables: dry bulb temperature, global solar irradiation on the horizontal and wind speed. It consists of hourly data, selected from approximately 20-year data sets (typically 1983-2004) and smoothed to provide a composite but continuous 1-year sequence of data (Levermore and Parkinson, 2006).

In contrast, DSY which is used for summertime overheating risk assessment in naturally ventilated buildings consists of an actual 1-year sequence of hourly data with a 'near extreme' warm summer (Hacker et al., 2009). The DSY is selected on the basis of the average dry bulb temperature over April-September period from the 20-year data. The year selected is the mid-year of the upper quartile for a source period of 20 years (i.e. the year with the third warmest April to September period). Having selected a particular year as the

DSY for a given location, the hourly data are for all 12 months of that year (Levermore and Parkinson, 2006; Hacker et al., 2009).

The procedure for selecting the months and the year for both TRY and DSY respectively for the 14 different locations across the UK is described in details in Levermore and Parkinson (2006). For Birmingham, which is the local weather of the case study, the selected years for each month used for TRY is shown in **Table 6.2** while the selected DSY is 1989 (CIBSE, 2006). However, both the TRYs and DSYs currently used by building designers do not take into account potential future climate change scenarios.

Table 6.2 Selected years for each month for Birmingham TRY
Source: (CIBSE, 2006)

Month	Year
January	2000
February	2004
March	2004
April	2000
May	1995
June	1983
July	2001
August	1996
September	1995
October	1988
November	1991
December	2000

As previously discussed in **Chapter 3** (**Section 3.6**), the UKCIP02 climate change scenarios give four different projections for climate change over the twenty-first century based on four different scenarios for greenhouse gas emissions: [Low, Medium-Low, Medium-High, and High emissions], over three time slices: [2020s, 2050s, and 2080s] (Hulme et al., 2002).

Projections for changes in 'monthly' average weather variables are provided for each scenario based on a regional climate model of 50 km grid spacing. This makes it unsuitable for direct use in building performance simulation where TRYs and DSYs at hourly resolution are required (Jentsch et al., 2008; Hacker et al., 2009).

However, as indicated by Belcher et al. (2005), there are several possible methods to generate climate change weather data for building simulation from results of global or regional climate models. One of these methods is the adjustment of present day weather data with regional climate change model predictions, generally termed 'morphing'.

6.5.2   Morphing of Present-Day Weather

Belcher et al. (2005) have developed an approach for converting CIBSE TRY and DSY weather files into climate change weather years based on the UKCIP data output. Hourly CIBSE weather data for the present-day climate are adjusted with the monthly climate change prediction values of the UKCIP02 scenario datasets. This approach is termed 'morphing' due to the fact that it involves 'stretching' and 'shifting' the present-day observed time series to produce a new time series that has the monthly average statistics of the climate change scenario (Belcher et al., 2005).

The basic underlying approach for weather file 'morphing' operations that have been applied consists of three different algorithms depending on the weather parameter to be converted (Jentsch et al., 2008; Hacker et al., 2009):

- a 'shift' of a current hourly weather data parameter by adding the UKCIP02 predicted absolute monthly mean change

$$x = x_0 + \Delta x_m \qquad \text{Eqn 6.1}$$

  Where x is the future climate variables, x_0 the original present day variable and Δx_m the absolute monthly change according to UKCIP02. The shift operation is useful when the projected change in the climate change scenario is given as an absolute increment in the monthly mean value. Therefore, this method is, for example, used for adjusting atmospheric pressure.

- a 'stretch' of a current hourly weather data parameter by scaling it with the UKCIP02 predicted relative monthly mean change:

$$x = a_m x_0 \qquad \text{Eqn 6.2}$$

  Where a_m is the fractional monthly change according to UKCIP02. The stretch operation is useful when the scenario change is given as a percentage change in the monthly mean. Therefore, this method is for example applied for morphing the present-day wind speed, specific humidity and global irradiation.

- a combination of a 'shift' and a 'stretch' for current hourly weather data. In this method a current hourly weather data parameter is 'shifted' by adding the UKCIP02 predicted absolute monthly mean change and ' stretched' by the monthly diurnal variation of this parameter:

$$x = x_0 + \Delta x_m + a_m \left(x_0 - \langle x_0 \rangle_m \right) \qquad \text{Eqn 6.3}$$

Where $(x_0)_m$ is the monthly mean related to the variable x_0, and a_m is the ratio of the monthly variances of Δx_m and x_0. This type of operation is useful when additional change information is contained in the climate change scenario in addition to the monthly mean change. For example this operation is applied for adjusting the present- day dry bulb temperature. It uses the UKCIP02 predictions for the monthly change of the diurnal mean, minimum and maximum dry bulb temperatures in order to integrate predicted variations of the diurnal cycle.

Detailed information on the application of these 'morphing' equations on various CIBSE TRY/DSY weather data parameters is given in appendix A1 of Hacker et al. (2009).

6.5.3   Assessment of the Generated Weather Data

The morphing approach has been used in two research projects (e.g. CIBSE, 2005 and Jentsch et al., 2008) for generating climate change weather file due to the recognition of its usefulness. The resulting climate change files can be directly related to the current CIBSE TRY and DSY standard weather data used for building compliance test and that makes this approach particularly attractive.

However, this approach has some limitations. It assumes that the patterns of future weather (for example the intensity and duration of heat waves) will be the same as they are today, which may not be the case (Hacker et al., 2009). The produced future weather pattern is largely analogous to the present-day weather in terms of changes in diurnal cycles and extreme weather events such as heat waves. In addition to that, some variables are morphed independently, which means the relationships between variables in the new time series may

not be the same as those in the original time series. This is the case for temperature and humidity (Hacker et al., 2009).

Moreover, the current CIBSE TRY and DSY files used for morphing calculations were derived from weather data from 1983-2004 while the baseline time frame to which the relative changes of the UKCIP02 climate change scenarios compare is the period from 1961 to 1990. Therefore, 'morphing' results can be expected to somewhat overestimate climate change and are limited to the scope of the observations from 1983-2004 (Jentsch et al., 2008; Hacker et al., 2009).

Jentsch et al (2008) selected two current CIBSE/Met Office weather sites, London Heathrow and Norwich, in order to assess the potential climate change overestimates pointed out above. They concluded that the methodology of 'morphing' present-day CIBSE weather data with the UKCIP02 scenario data appears to reflect the overall UKCIP02 climate change modelling predictions reasonably well (Jentsch et al., 2008). No significant overestimation of climate change due to the different baseline timeframes could be determined. However, what is not covered by such 'morphed' weather files is the impact of localised future environmental changes and microclimate effects such as human settlements (urban heat island effect), local land use or effects of anthropogenic activities (Hacker et al., 2009). On the other hand, the advantage of this approach is that the generated data are likely to be meteorologically consistent (Jentsch et al., 2008).

6.6   Thermal Comfort Criteria

In line with recent CIBSE guidance (CIBSE, 2006) Muirhead Tower was said to have overheated if in any 1 year 1 % of occupied hours exceeded 28°C. The strategy to control

summer overheating is that when it becomes warm inside the building occupants will open windows. In the computer model, the occupants begin to open windows when the indoor temperature exceeds 24°C to allow cooler external air to enter and avoid overheating in summer. Otherwise windows will be closed at all other times when the above conditions are not achieved. This will ensure utilizing the external air as a source of cooling for the space.

The ventilation rate when windows are closed is the background fabric infiltration (1 air change per hour) to provide the necessary minimum fresh air change rate for occupant health (CIBSE, 2006). When windows are open, they are open fully and the maximum ventilation rate corresponding to fully open windows was taken to be 6 air changes per hour. Air change per hour (ach) is the movement of a volume of air (equals to the volume of the room) in a given period of time; if a room has 6 ach, it means that the air in the room will be replaced 6 times in a one-hour period (CIBSE, 2005). Previous research has shown that there is little further benefit beyond 6 ach in buildings (CIBSE, 2005).

24°C was chosen to represent the temperature above which most occupants start to feel warm and uncomfortable and this is in line with CIBSE recommendations for summer indoor comfort temperatures in non air-conditioned buildings (CIBSE, 2006). However, it should be noted that according to the adaptive comfort theory (**Chapter 5 Section 5.3.2**), which is supported by case study examples, comfort temperatures change with the prevailing conditions and therefore, higher temperatures inside buildings may be more acceptable as climate change progresses (Jentsch, 2008).

In the future, comfort expectations are likely to change in ways which are not predictable at the present time (Hacker et al., 2008). However, current standards have been used for the comparisons (CIBSE, 2006) i.e. it is assumed that in the future the occupants will still think

28°C is unacceptable regardless of climate change and the ability to adapt to higher temperatures.

6.7   Energy Usage and CO_2 Emissions

Building Regulations provide detailed standards for energy use in new and existing buildings for heating, ventilation and cooling through Approved Document L: Conservation of fuel and power (ODPM, 2006). CIBSE guide 'F' provides benchmark values for typical (existing building) and best practice (new-build) energy use in different building types (CIBSE, 2004). However, in practice, energy use in buildings has been found to differ broadly across buildings of similar type due to differences not only in the design purpose, envelope and systems but also in the mode of use, control and maintenance of services and standard of construction and airtightness (CIBSE, 2005).

Moreover, energy consumption experienced in practice can vary from that calculated at the design stage depending on the computer modelling used. This does not mean that a modelling approach is not appropriate for building performance assessment but this limitation highlights the difference between actual and assumed system, usage, weather conditions and other contributing factors (CIBSE, 2005).

Rather than the use of fixed targets, relative energy consumption and CO_2 emissions of different refurbishment solutions comparing to the 'as built' case have been considered to be indicative of changes in future performance.

In order to minimise cooling energy, the strategy adopted here is that mechanical cooling is only considered when the refurbishment options fail to provide the suggested comfort level to the building. Therefore, the systems used here are only active when the space temperature

rises above 28°C after using different refurbishment solutions. Under these conditions, all openings were closed and a cooling load calculated for the period during which the internal temperature remained at or above this value. A cooling set point is selected to be 23°C in the rooms (this is the indoor comfort temperature threshold where 80% of people are satisfied at an outside temperature of 28°C, based on **Figure 5.2** page 100 and the industry standards) (CIBSE, 2005). Clearly, different cooling set points result in different cooling energy consumptions but because relative performance was compared in this study, it was not necessary to set fixed cooling energy consumption targets.

CO_2 emissions from different energy using components of the building have been calculated based on an assumed mix of fuel types. The energy sources and CO_2 emission factors assumed were:

- Heating- natural gas- 0.194 kg CO_2 / kWh

- Cooling - electricity- 0.422 kg CO_2 / kWh

These figures are those used in the 2006 issue of the UK Building Regulations (ODPM, 2006). It is inevitable in the future that these values will change (Hacker et al., 2008). However, as it is not possible to say in what or which way, a decision was made to use the present-day emission figures.

6.8   Validation of the Model

To validate simulation models, the results from their use are normally compared with measured (observed) data (Sargent, 2007). For this study, this approach is not possible since the energy metering system for Muirhead Tower is connected to other buildings at the University of Birmingham campus. Therefore, reliable results regarding the actual gas or electricity consumption were not available. In this study, the model used investigates three different kinds of rooms within Muirhead Tower, with different equipment use and occupancy. Therefore, even if the total gas and electricity consumption readings of whole of Muirhead Tower were available, they would not give data for each room which would be required for a true comparison.

For the reasons outlined above, CIBSE energy consumption benchmarks (**Table 6.3**) for cellular, open-plan and teaching room have been used for comparison with the simulated results (CIBSE, 2004). The gas and electric energy consumption results from the simulation model for the selected rooms are shown in (**Table 6.4**).

Table 6.3 Fossil and electric building benchmarks for the three selected rooms
Source: (CIBSE, 2004)

Room type	Energy consumption benchmarks (kWh/m^2 per year)			
	Lower limit		Upper limit	
	Gas	Electricity	Gas	Electricity
Cellular office	79	33	151	54
Open-plan office	79	54	151	85
Teaching room	100	29	120	39

Table 6.4 Simulated energy consumption for the three selected rooms

Room type	As-built simulated energy consumption (kWh/m^2 per year) under the present day climate (2005)							
	North façade		South façade		East façade		West façade	
	Gas	Electricity	Gas	Electricity	Gas	Electricity	Gas	Electricity
Cellular office	142	53	106	53	127	53	130	53
Open-plan office	128	97	93	97	113	97	116	97
Teaching room	42	44	37	44	40	44	40	44

For the cellular office, the simulated gas consumption for the north and south façade is 142 kWh/m^2 per year and 106 kWh/m^2 per year respectively (**Table 6.4**). Results for the other façades fall within the range for the north and south façades. These values for energy consumption fall within the range of CIBSE benchmark (79-151) kWh/m^2 per year for these types of rooms (**Table 6.3**). For electricity consumption, the simulated result is 53 kWh/m^2 per year (**Table 6.4**) which is slightly lower than the upper limit (**Table 6.3**) for these kinds of rooms (54 kWh/m^2 per year).

For the open-plan office, the simulated gas consumption for the north and south façades is 128 kWh/m^2 per year and 93 kWh/m^2 per year respectively (**Table 6.4**). Results for the other façades fall within the range for the north and south façades. Similar to the cellular office, the simulated gas and electricity consumption falls within the range of CIBSE benchmarks (**Table 6.3**).

For the teaching room, while the simulated electricity consumption (**Table 6.3**) for different orientations is slightly higher than the upper limit of CIBSE benchmarks (**Table 6.4**); the simulated gas consumption is significantly lower than the CIBSE benchmarks range (**Table 6.4**). This can be explained by the fact that the teaching room has a very low glazing ratio (10 %) which results in low solar heat gain, however, this is more than offset by reduced losses by conduction. Moreover, the teaching room has a high density occupancy which results in high internal gain. For these reasons, the simulation shows reduced total heating energy (gas) requirements compared to the CIBSE benchmarks (**Table 6.3**).

To support this hypothesis, the glazing ratio of the teaching room was changed to 55% (same as open plan office) to allow comparison since the open-plan office and teaching room have the same wall area and hence same solar gain. The gas and electric energy consumption results for the modified simulated teaching room are shown in **Table 6.5**. The values for the gas consumption for the modified teaching room are less than the open-plan room (**Table 6.4**) since the total internal gains (e.g. from occupants and equipment) for the teaching room is more than the open-plan room (**Table 6.1**).

However, the simulated results for gas consumption for the modified teaching room for different orientations (85-115 kWh/m^2 per year) are close to the CIBSE benchmarks (100-120 kWh/m^2 per year) [**Table 6.5**]. Therefore, these comparisons suggest that the computer model provides a realistic representation of likely energy demand and can be used to investigate the relative performance of different refurbishment options under different climate change scenarios.

Table 6.5 Simulated energy consumption for teaching room assuming 55 % glazing ratio

As-built simulated energy consumption (kWh/m^2 per year) under the present day climate (2005) for teaching room assuming 55% glazing ratio							
North façade		South façade		East façade		West façade	
Gas	Electricity	Gas	Electricity	Gas	Electricity	Gas	Electricity
115	44	85	44	94	44	97	44

6.9   Refurbishment Options

Refurbishment schemes applied within existing buildings are required to comply with specified parts of the Building Regulations, including Part L (Conservation of Fuel and Power, which includes thermal insulation requirement) (ODPM, 2006).

For existing HE buildings which are considered as non domestic building, part L2B in building regulations (Conservation of fuel and power in existing buildings other than dwellings) should be followed.

When the thermal elements of the building are being refurbished, the Building Regulations consider that it is necessary to upgrade elements of the building that have U-values worse than those shown in **Table 6.6**. The Regulations require the improved standards to comply with or be better than those set out in **Table 6.6**.

Table 6.6 U-value Standards for replacement thermal elements (W/m^{2}K)
Source: (ODPM, 2006)

Building element	U-value standards for replacement thermal elements, W/m^{2}K
Wall	0.35
Pitched roof-insulation at ceiling level	0.16
Pitched roof-insulation at rafter level	0.20
Flat roof or roof with integral insulation	0.25
Floors	0.25
Windows, roof lights and roof windows	2.0 for the whole unit OR 1.20 centre pane
Doors with 50% or greater of their internal area glazed	2.20
Other doors	3.0

Table 6.1 shows that Muirhead Tower's thermal performance values for different components (e.g. walls and windows) do not comply with the current Building Regulations [2006] (ODPM, 2006).

The U-value for the external walls of Muirhead Tower is 1.5 W/m^{2}K [as-built] compared with 0.35 W/m^{2}K [current Building Regulation] (**Table 6.6**), while the U-value for its glazing is 5.3 W/m^{2}K [as-built] compared with 2.0 W/m^{2}K [current Building Regulation].

However, since Building Regulations related to the conservation of fuel and power have been regularly revised and are expected to become tighter with every revision, two types of

each refurbishment option are considered. One which represents the current minimum Building Regulation requirement and the other represents the best insulation option available in the market (above the minimum requirement) which is likely to be used for future building regulations in 2050 and 2080. That would help also to observe the impact of improving the thermal performance of individual elements on overall energy consumption, CO_2 emissions and thermal comfort.

This analysis assumes that each refurbishment option is installed in a way that maximises its effectiveness. In reality, this is likely to prove difficult and even small variations from ideal installation conditions can have a significant impact on the relative effectiveness of different refurbishment options (Roaf et al., 2008).

Refurbishment options considered in this study include:

- Wall Insulation

Due to the difficulty of applying external insulation to retain the historic façade, it was decided to apply internal insulation. Currently, the most common approach to internal insulation in industry is to apply dry lining comprising plasterboard with a layer of rigid insulation pre-bonded to it. 'Kingspan Kooltherm' insulated dry-lining board [phenolic foam board] (**Figure 6.5**) is a good example of this proprietary system (Gorse and Highfield, 2009).

This system is available in a variety of sizes. The plasterboard thickness is 12.5 mm, with insulant thicknesses varying from 20 mm to 70 mm thick in increments of 5 mm. When applied to the existing Muirhead Tower walls, a 57.5 mm thick board (45 mm insulation, 12 mm plasterboard) achieves a U-value of 0.35 W/m^{2}K while 82.5 mm thick board (70 mm

insulation, 12 mm plasterboard) achieves a U-value of 0.15 W/m²K (Gorse and Highfield, 2009).
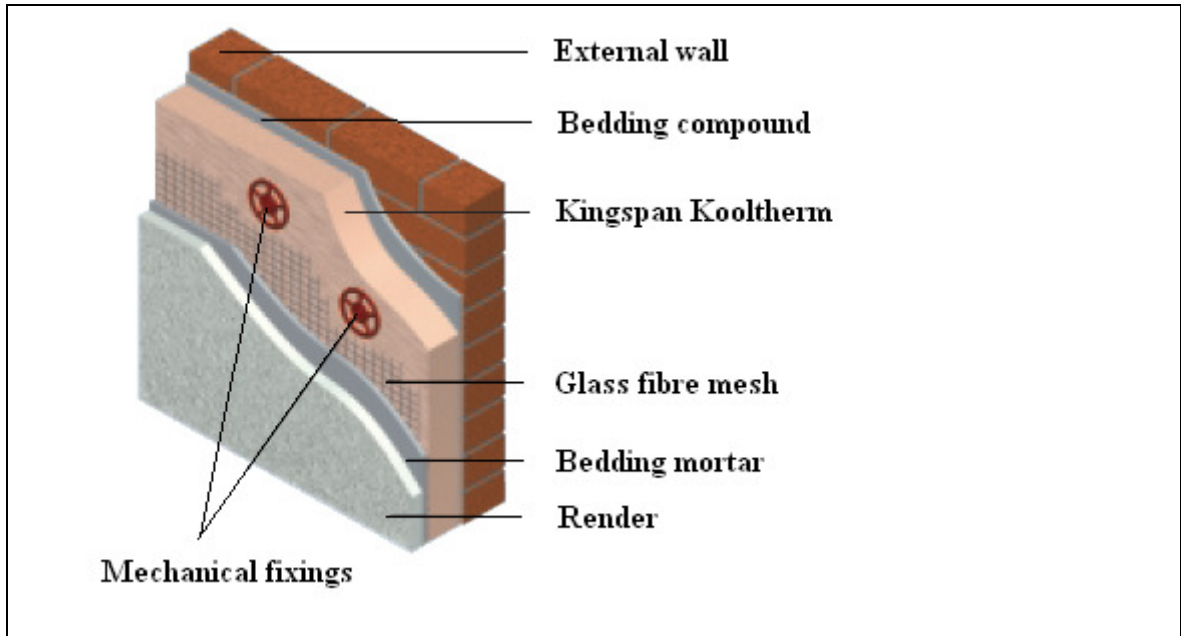
Figure 6.5 Application of Kingspan Kooltherm as an internal insulation
Source: (Kingspan, 2010)

- Windows Replacement

For windows, 'Pilkington glazing units' have been used to replace existing windows (**Figure 6.6**). The use of low e- double glazing curtain walls (4 mm Optifloat / 12 mm air / 4 mm Pilkington K glass) achieves a U-value of 2.0 W/m²K which comply with the current Building Regulations requirements (**Figure 6.6a**) while triple glazing (4 mm Optiwhite / 12 mm krypton / 4 mm Pilkington K glass / 12mm krypton / 4 mm Pilkington K glass) achieves a U-value of 0.70 W/m²K (**Figure 6.6b**) (Pilkington, 2009).
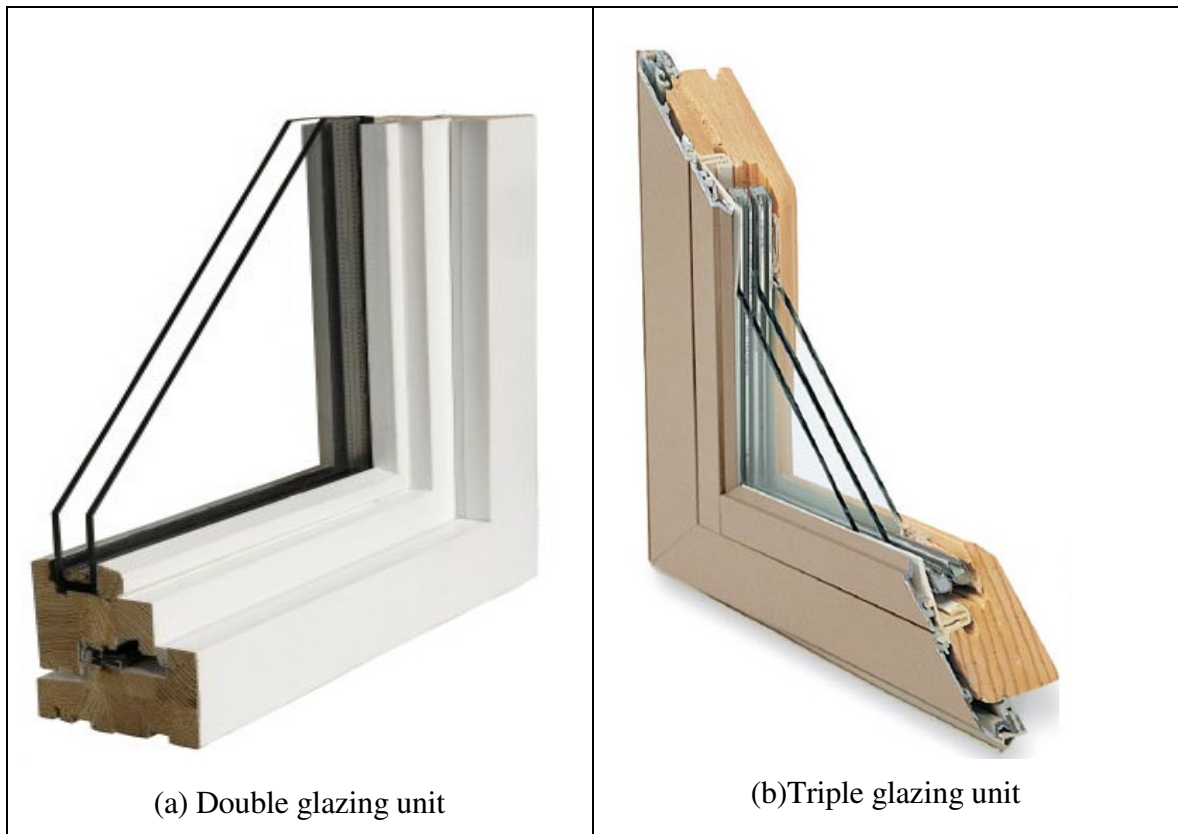
Figure 6.6 Pilkington glazing units
Source: (Pilkington, 2009)

- Shading system

For shading, Building Regulations did not specify any shading coefficient (ODPM, 2006). However, as discussed in **Chapter 5**, external shading is used since it is more effective than internal shading. 'Koolshade system' has been chosen (**Figure 6.7**) since it has been used in a number of commercial projects in the UK and appeared to be a thermally efficient and cost effective solution (Koolshade, 2009). Each Koolshade screen is made up of hundreds of little louvres, each inclined at 27° (Koolshade, 2009).

When the Sun's rays travel in a straight line at dawn and dusk when the Sun is at an angle of 0°, light and heat enter directly into the building. As the Sun rises in the sky, the screens

block out the detrimental effects of the Sun. Once the Sun reaches an angle of 40°,

Koolshade blocks 100% of the Sun's direct rays (**Figure 6.8**).

Figure 6.7 Using Koolshade system in Muirhead Tower
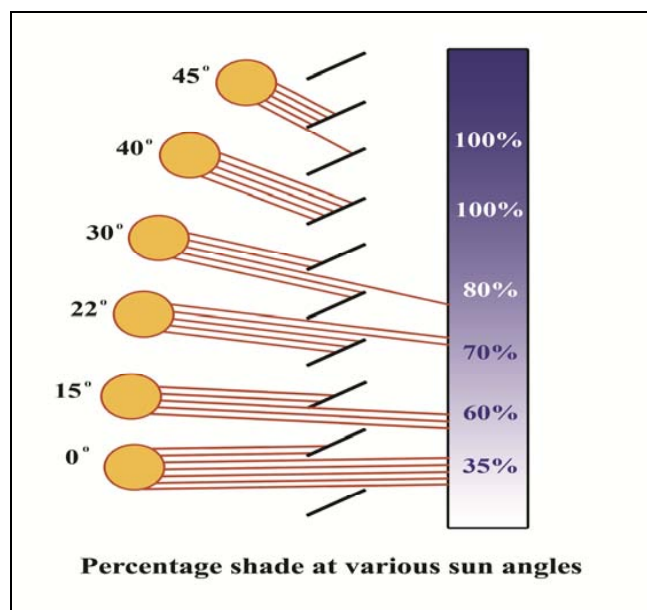
Figure 6.8 Koolshade system
Source: (Koolshade, 2009)

Two more options have been considered; one which combines all refurbishment options which comply with current Building Regulation requirements while keeping air infiltration as 1 ach, while the other option would be a combination of all the previous options but would result in improvement of air infiltration to 0.25 ach to comply with current air infiltration regulations.

The model was run for the 'baseline' [i.e. the present day (2005)] as well as the 2020s, 2050s and 2080s under low and high emission scenario. It should be noted here that the 2050s can be expected to represent the end of the building's design life after refurbishment (Mulligan and Steemers, 2002). However in this work, full climate change assessment using weather files of all three timeslices under low and high UKCIP02 emission scenarios has been considered to provide a comparative analysis. The building was modelled in two different ways. The first case, 'as built' represents the building as it was originally designed and is likely to be used currently. The second case, 'adapted or after applying each refurbishment option', represents the building as it might exist when adapted to improve its performance using different refurbishment options under the current and future climate change scenarios.

The investigation was based upon a set of performance criteria, previously explained, and because relative performance of refurbishment options was the main interest, it was not essential to set absolute targets in terms of energy consumption or CO_2 emissions.

6.10   Results

The assessment of the case study building was made using Birmingham TRY weather files for energy consumption and DSY weather files for overheating assessment produced by CIBSE using the morphing methodology that was discussed earlier. The output provided by the computer modelling is hourly values of indoor temperature in each room using DSY weather files and a prediction for the energy consumption of the heating and cooling using TRY weather files. From the energy consumption predictions, CO_2 emissions can be calculated using an assumed mix of fuel types.

6.10.1 As-Built Performance

As-built performance results are presented in **Figures 6.9-6.11**. They show the predicted hours at which operative temperatures exceed 28°C expressed as a percentage of the occupied hours in the year for different orientations of different rooms for the present day climate, and for the future climate under low and high emission scenarios. A greater than 1 % exceedance of 28°C threshold is taken to indicate 'overheating'. As would be expected with the predicted increase in the external temperature due to climate change, the period when the ambient room temperature is above 28°C increases for different orientations and for different rooms. Results from the thermal analysis highlight the sensitivity of different orientations to alternative climate scenarios.
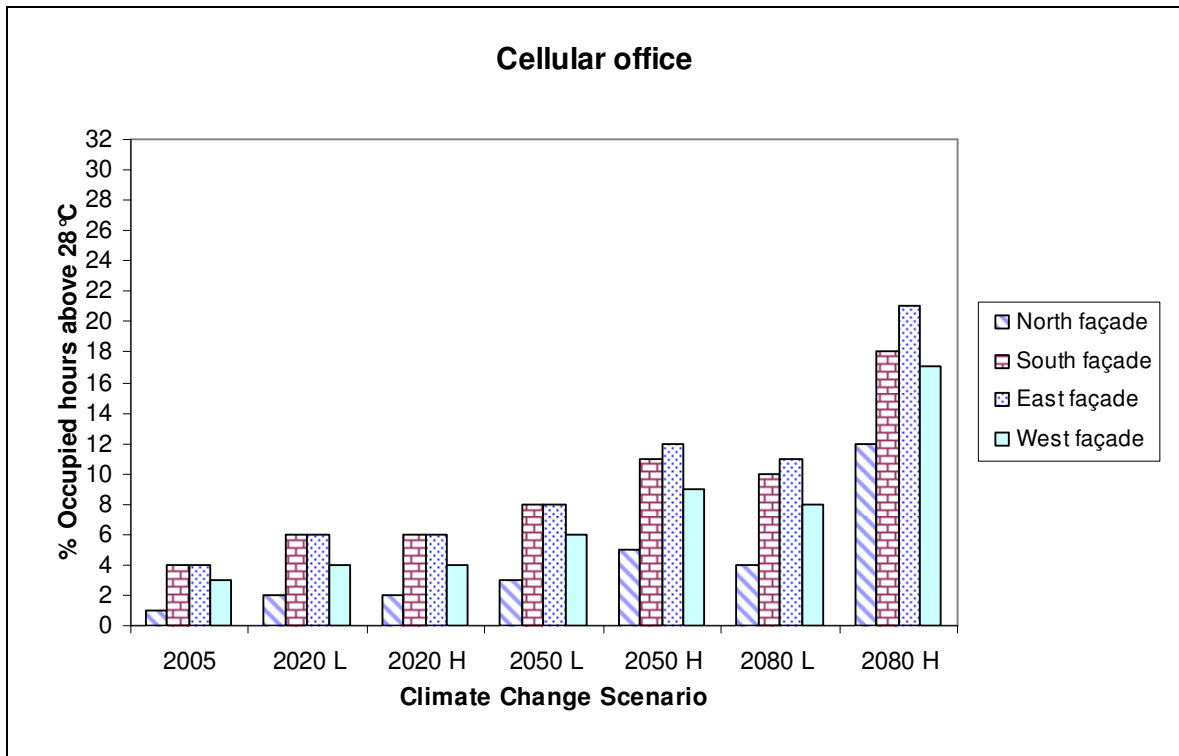
Figure 6.9 Predicted hours of exceedance of operative temperature of 28°C for different orientations of the cellular office under the Birmingham DSYs for the present-day (2005) and for the UKCIP02 Low and High emissions scenarios
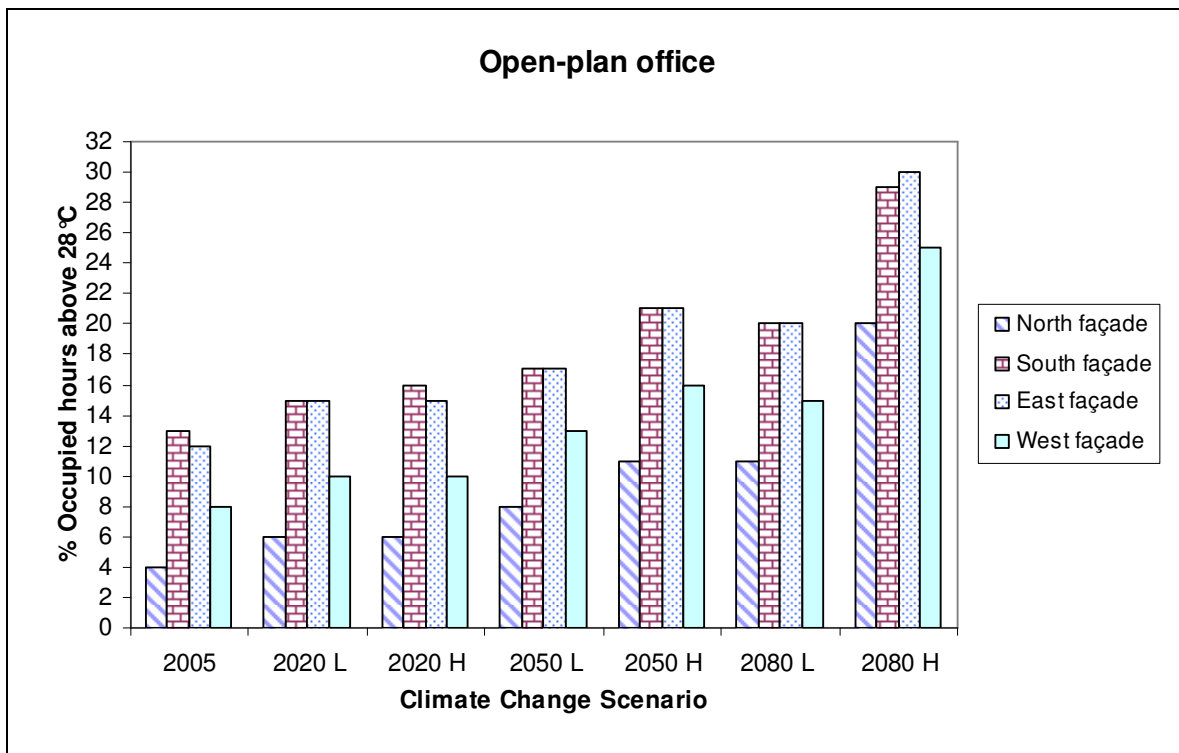
Figure 6.10 Predicted hours of exceedance of operative temperature of 28°C for different orientations of the open-plan office under the Birmingham DSYs for the present-day (2005) and for the UKCIP02 Low and High emissions scenarios
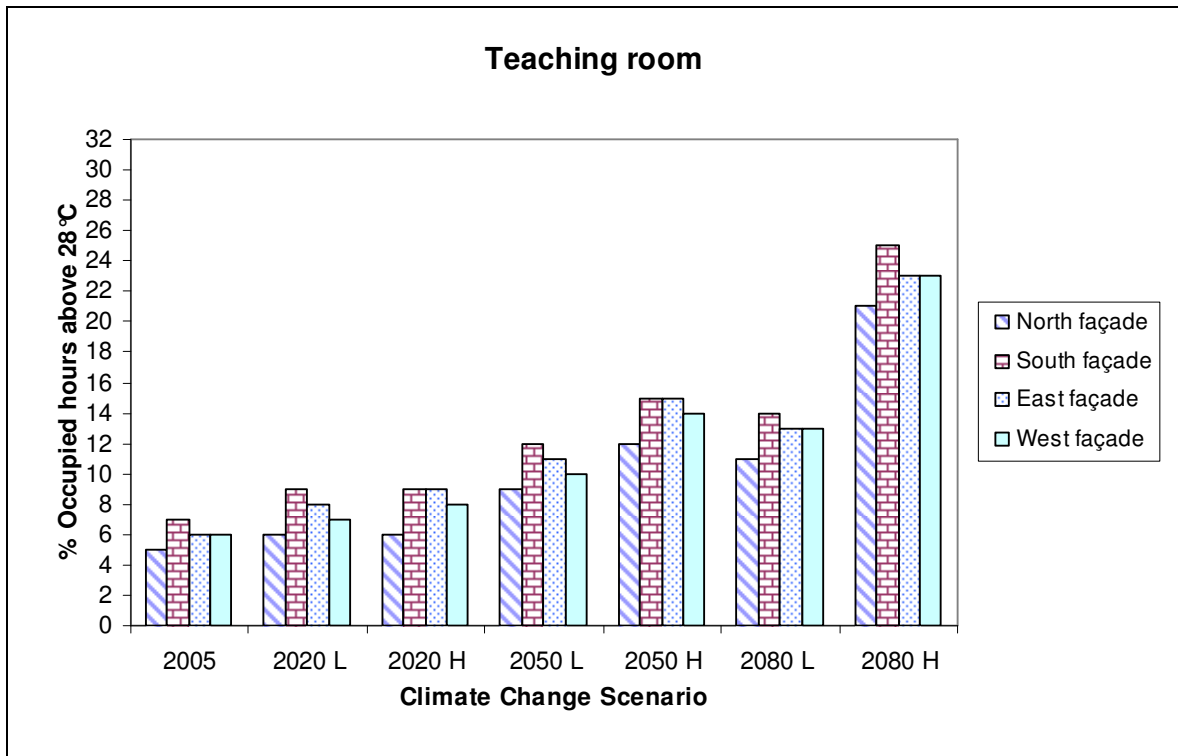
Figure 6.11 Predicted hours of exceedance of operative temperature of 28°C for different orientations of the teaching room under the Birmingham DSYs for the present-day (2005) and for the UKCIP02 Low and High emissions scenarios

In terms of thermal performance, the south and east façade show similar behaviour, although the number of hours above 28°C is slightly higher for the east façade in cellular and open-plan offices. The north façade receives the least solar gain among the different orientations.

For east facing cellular offices, overheating becomes common, increasing from 4 % of occupied hours in the present to 21 % of occupied hours under the high emission scenario in the 2080 timeslice. For the north facade only 1 % of the occupied hours are over 28°C in the present-day which meets the comfort criteria but by the 2020 timeslice this has increased to 2 % of occupied hours, increasing further in subsequent timeslices to reach 12 % under the high emission scenario in 2080. Results for the other orientations fall within the range for the north and east façades (**Figure 6.9**).

The open-plan office performs worse than the cellular office due to the higher glazing ratio, higher density of occupation and IT equipment with 12 % of occupied hours over 28°C in the present-day, increasing to around 30 % under the high emission scenario of the 2080s for the east facade. Although the north façade receives less solar gain, it suffers from summertime overheating even in the present-day with 4 % of occupied hours over 28°C, increasing to approximately 20 % of occupied hours under the high emission scenario in 2080. Results for the other orientations fall within the range for the north and east façades (**Figure 6.10**).

The teaching room performs slightly worse than open-plan room for north façade due to higher density of occupation with 5 % of occupied hours in the present-day above 28°C rising to 21 % under the high emission scenario in 2080s compared with 4 % and 20 % for the open plan office. On the other hand, the teaching room performs better for all other orientations due to the lower glazing ratio which results in less solar gain and therefore less internal gain in total (**Figure 6.11**).

6.10.2 Refurbishment Options Performance Compared With As-Built Case

Performance results for different refurbishment options compared to the as built are presented in (**Figures 6.12-6.15**) for cellular office and for different orientations using Birmingham DSY weather files. Applying wall insulation and improving the glazing system would result in significant increase in number of hours above 28°C compared to the as-built case for different orientations.

(Cellular office, North facade)
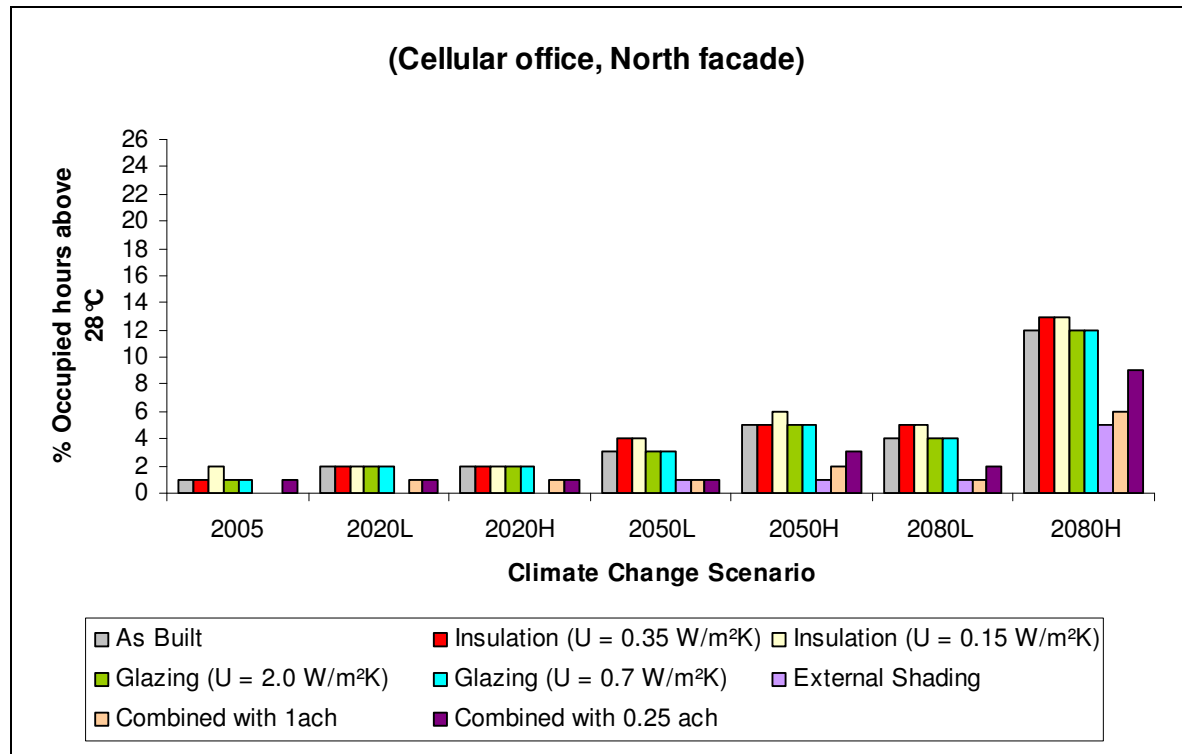
Figure 6.12 Predicted hours of exceedance of operative temperature of 28°C for the north orientation of the cellular office and for different refurbishment options under the Birmingham DSYs for the present-day (2005) and for the UKCIP02 Low and High emissions scenarios

(Cellular office, South facade)
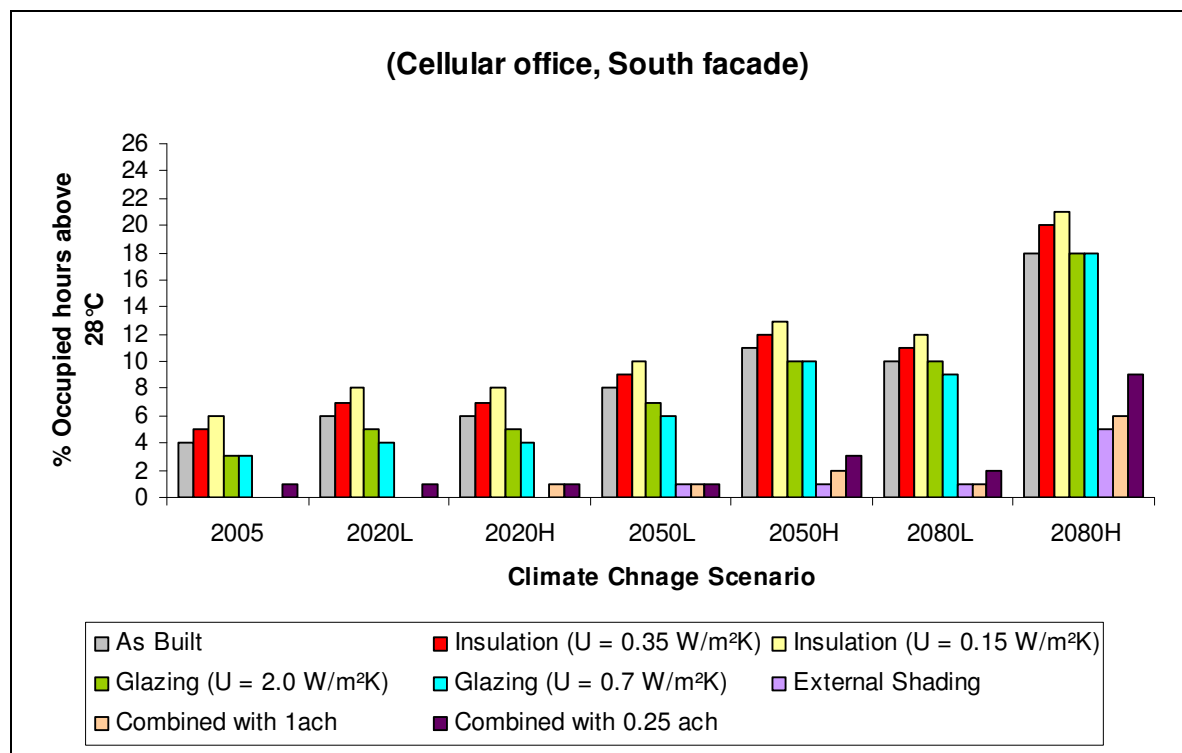
Figure 6.13 Predicted hours of exceedance of operative temperature of 28°C for the south orientation of the cellular office and for different refurbishment options under the Birmingham DSYs for the present-day (2005) and for the UKCIP02 Low and High emissions scenarios
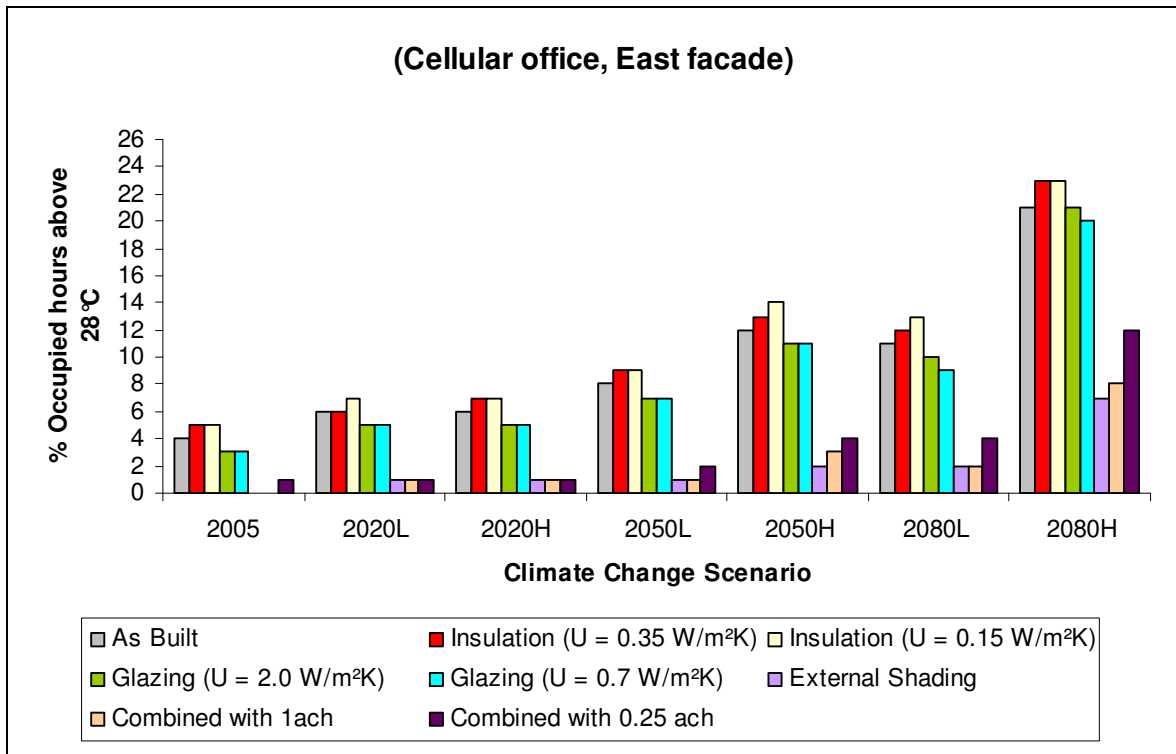
Figure 6.14 Predicted hours of exceedance of operative temperature of 28°C for the east orientation of the cellular office and for different refurbishment options under the Birmingham DSYs for the present-day (2005) and for the UKCIP02 Low and High emissions scenarios
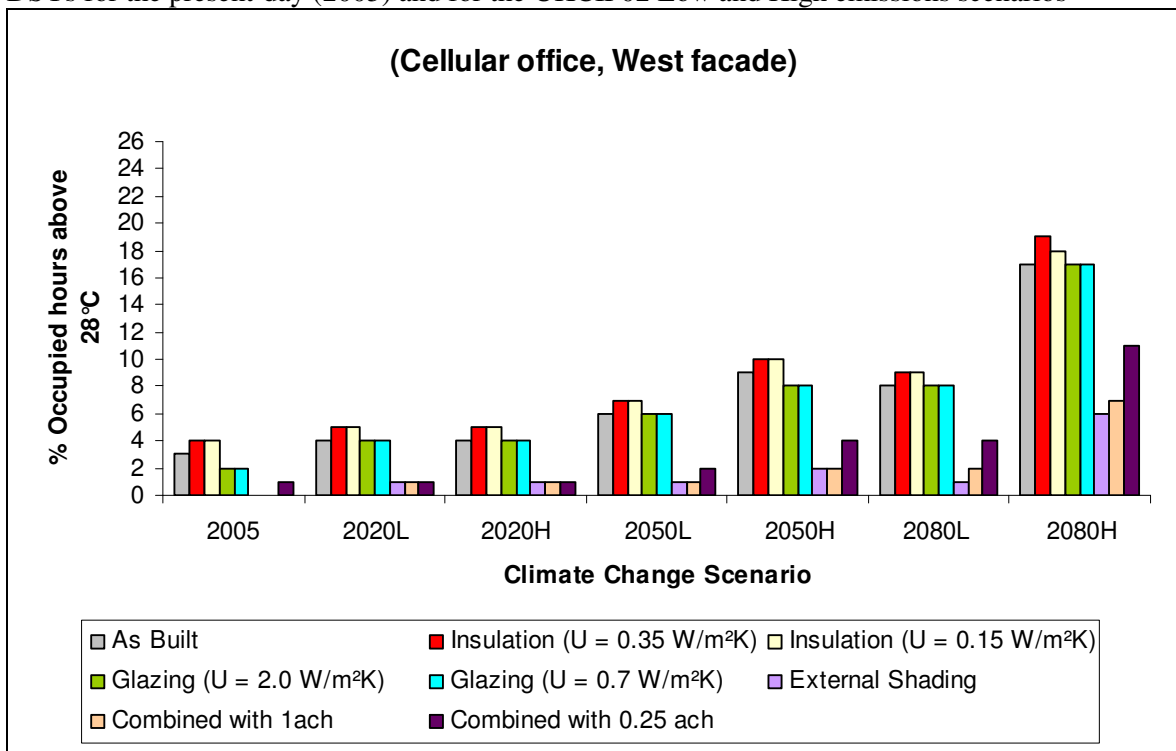
Figure 6.15 Predicted hours of exceedance of operative temperature of 28°C for the west orientation of the cellular office and for different refurbishment options under the Birmingham DSYs for the present-day (2005) and for the UKCIP02 Low and High emissions scenarios

For example, for the north facing cellular office (**Figure 6.12**) using wall insulation as a refurbishment solution, 2 % of occupied hours are over 28°C in the present-day increases to around 13 % under the high emission scenario in the 2080 timeslice compared with 1 % and 12 % respectively for the as-built case. For the east façade (**Figure 6.14**) 5 % of occupied hours in the present-day increases to 23 % under the high emission scenario in the 2080 timeslice compared with 4 % and 21 % respectively for the as-built case. Results for other orientations fall within the range for the north and east façades. No significant difference in performance between insulation with U-value of 0.35 W/m^{2}K and 0.15 W/m^{2}K is apparent in (**Figure 6.12-6.15**).

Windows replacement performs slightly better than wall insulation with less number of hours above 28°C but more than the as-built case. For the north façade, 1 % of occupied hours in the present-day are above 28°C increases to 12 % under the high emission scenario in 2080 timeslice (**Figure 6.12**). For the east façade, 3 % of occupied hours in the present-day are above 28°C increases to 20 % under the high emission scenario in 2080 (**Figure 6.14**). Results for the other orientations fall within the range for the north and east façades. No significant difference in performance between windows with U-values of 2.0 W/m^{2}K and 0.7 W/m^{2}K is apparent in (**Figures 6.12-6.15**).

External shading performs the best compared to the other refurbishment options. No overheating occurs under the present-day using external shading for all orientations (**Figure 6.12-6.15**), while acceptable overheating occurs in 2020s and 2050s for all orientations. Significant overheating would occur under the high emission scenario in 2080 timeslice with 5 % of occupied hours being above 28°C for the north façade (**Figure 6.12**) compared with 7

% for the east façade (**Figure 6.14**). Results for the other orientations fall within the range for the north and east façades.

The combination of all options with 1 ach has a similar performance to the external shading in all orientations until the 2050s. In the 2080s timeslice the 'combined all' option performs slightly worse than external shading.

However reducing air infiltration to around 0.25 ach generally performs very well up until 2050s, but from then on significant levels of overheating are predicted. For the north orientation (**Figure 6.12**), only 1 % of occupied hours are above 28°C in the present-day increases to 9 % under the high emission scenario of 2080 timeslice compared with 1 % and 12 % respectively for the east orientation (**Figure 6.14**). Results for the other orientations fall within the range for the north and east façades. Results for open-plan office and teaching room are shown in **Appendix A** due to the space constraints.

For the open-plan office (**Appendix A1**), external shading performs the best (i.e. least percentage of occupied hours above 28°C) compared to the other refurbishment options for different orientations and under different climate change scenarios, while triple-glazed windows (U-value = 0.70 W/m^{2}K) performs the worst. For the teaching room, external shading performs the best compared to the other refurbishment options, while 'combined all with 0.25 ach' option performs the worst (**Appendix A2**).

6.10.3 Heating Load

Figures 6.16-6.19 present the predicted heating loads in the cellular office under the low and high emissions scenarios and for different refurbishment options using Birmingham TRY weather files. As expected, the heating load is reduced significantly as a result of climate change. The north façade presents the highest relative heating demand with 142 kWh/m^2 under the present-day decreases to 90 kWh/m^2 under the high emission scenario in 2080 timeslice (**Figure 6.16**), whereas the south façade shows the lowest relative heating demand of 106 kWh/m^2 and 60 kWh/m^2 respectively in the as-built condition (**Figure 6.17**). Results for the other orientations fall within the range for the north and south façades.

If a single refurbishment solution was to be selected for thermal modification in the cellular office, then replacing single glazed windows with triple glazing (U-value = 0.70 W/m^{2}K) would give the best result. For the north orientation and by using triple glazed window (U-value = 0.70 W/m^{2}K), heating demand is reduced from 142 kWh/m^2 to 72 kWh/m^2 or 51 % of the as-built consumption in the present-day and from 90 kWh/m^2 to 43 kWh/m^2 or 48 % of the as-built consumption under the 2080s high emission scenario (**Figure 6.16**). For the south orientation, heating demand is reduced from 106 kWh/m^2 to 50 kWh/m^2 or 47 % of the as-built consumption in the present-day and from 60 kWh/m^2 to 26 kWh/m^2 or 43 % of the as-built consumption under the 2080s high emission (**Figure 6.17**). Results for the other orientations fall within the range for the north and south façades.
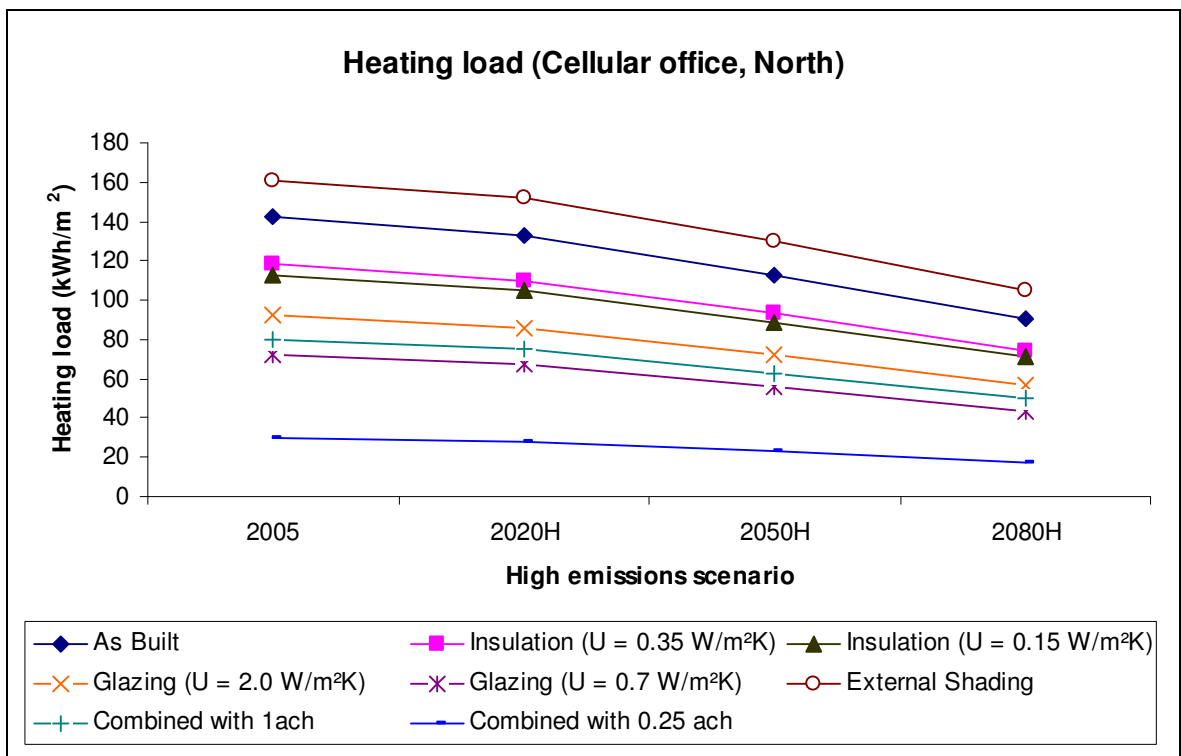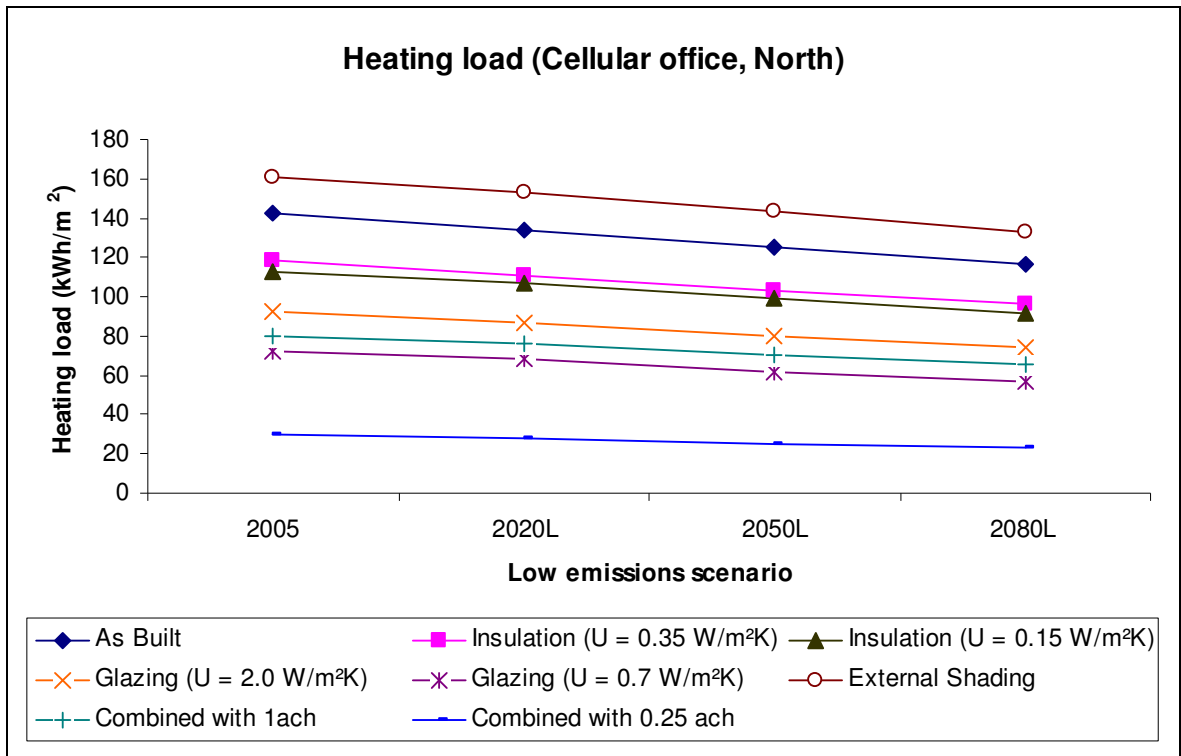
Figure 6.16 Heating loads under low and high emission scenarios for the north façade of the cellular office
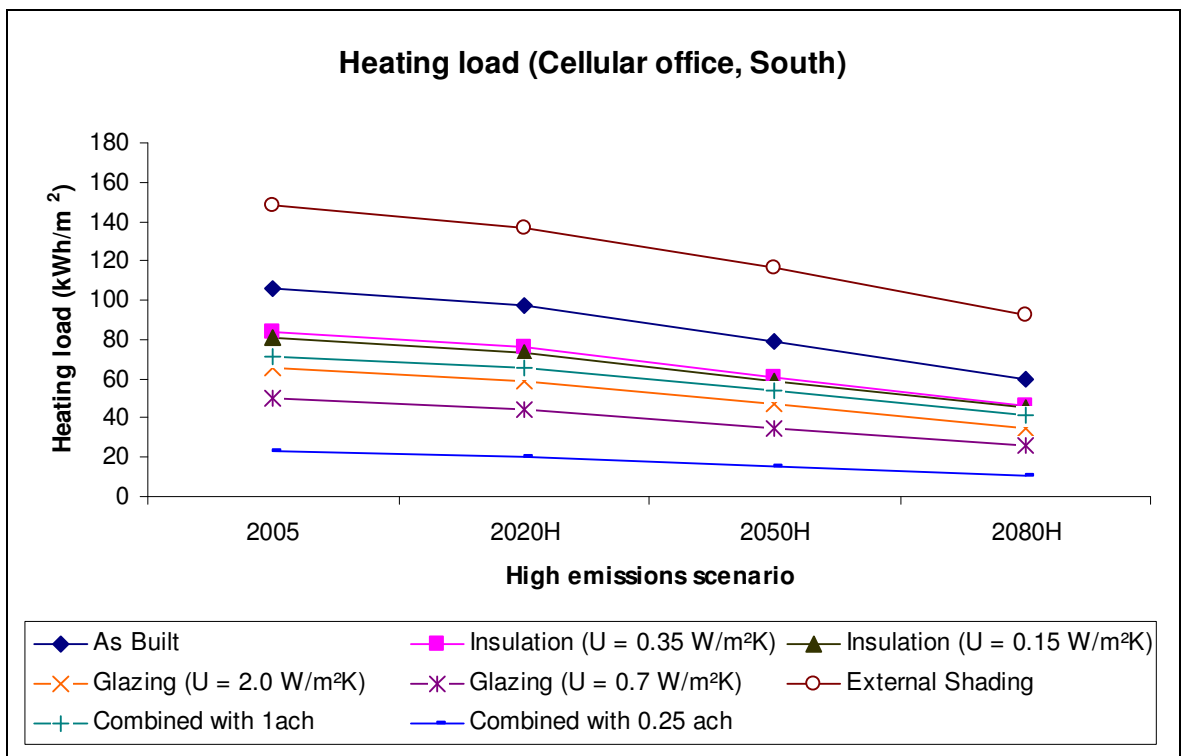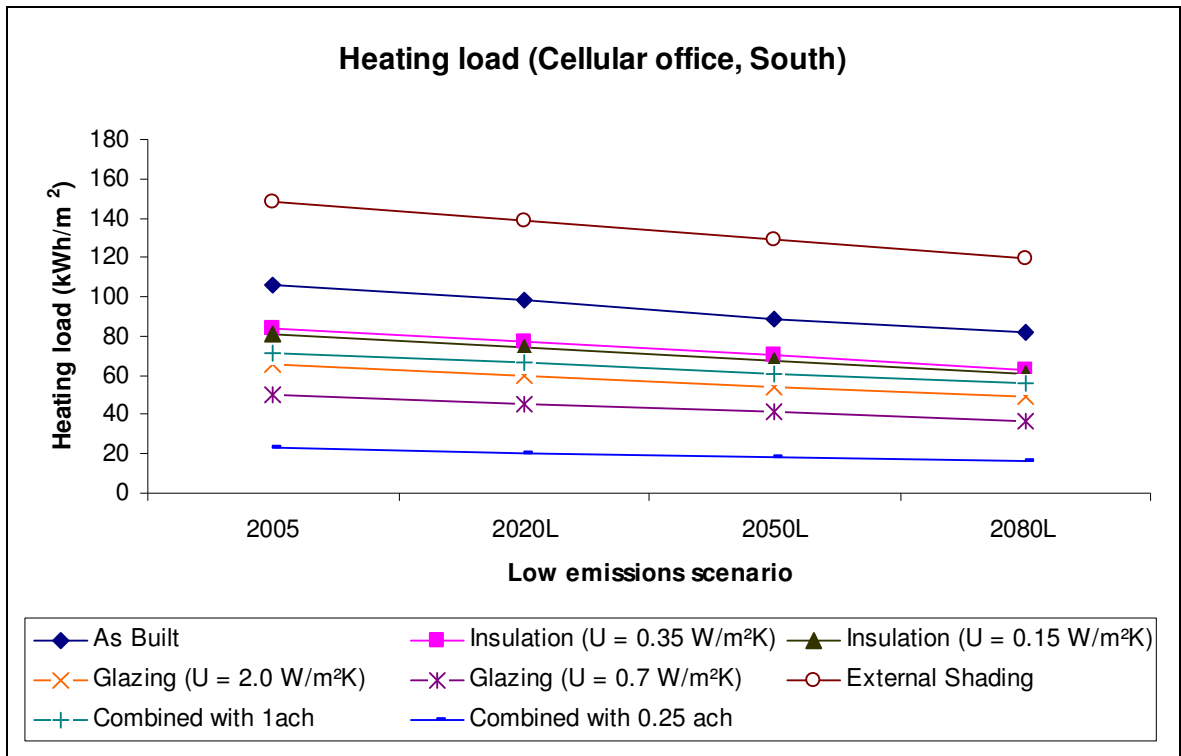
Figure 6.17 Heating loads under low and high emission scenarios for the south façade of the cellular office
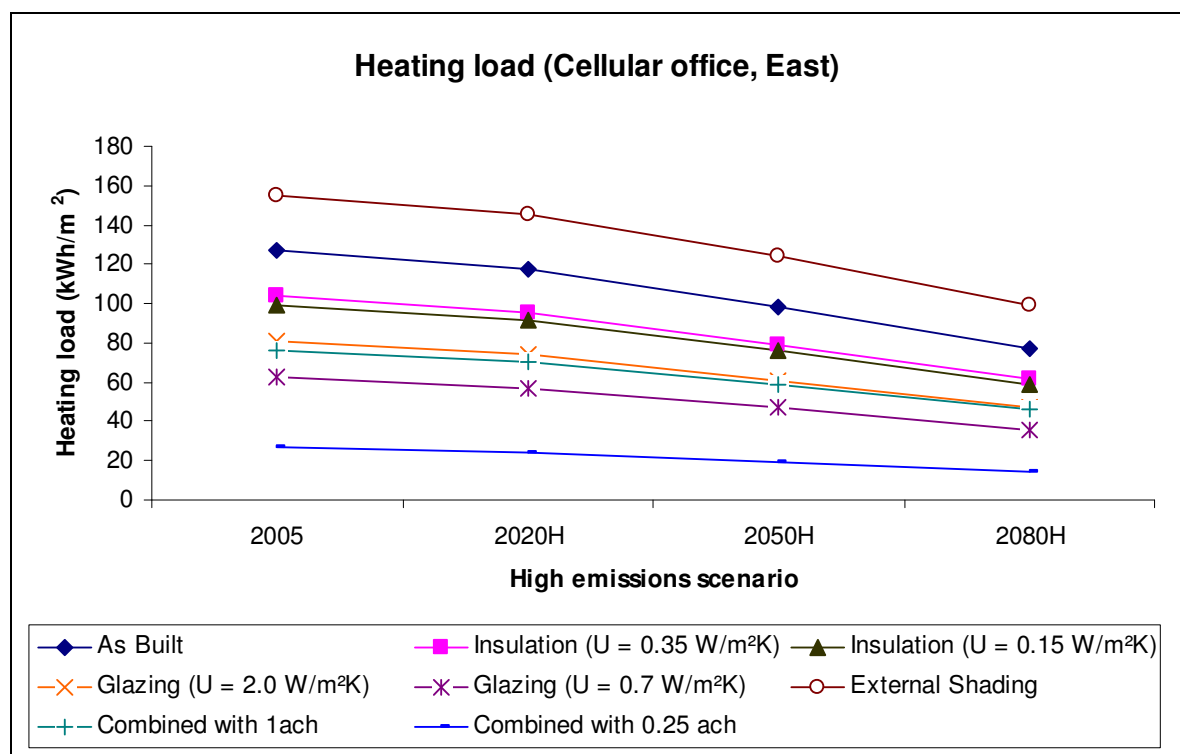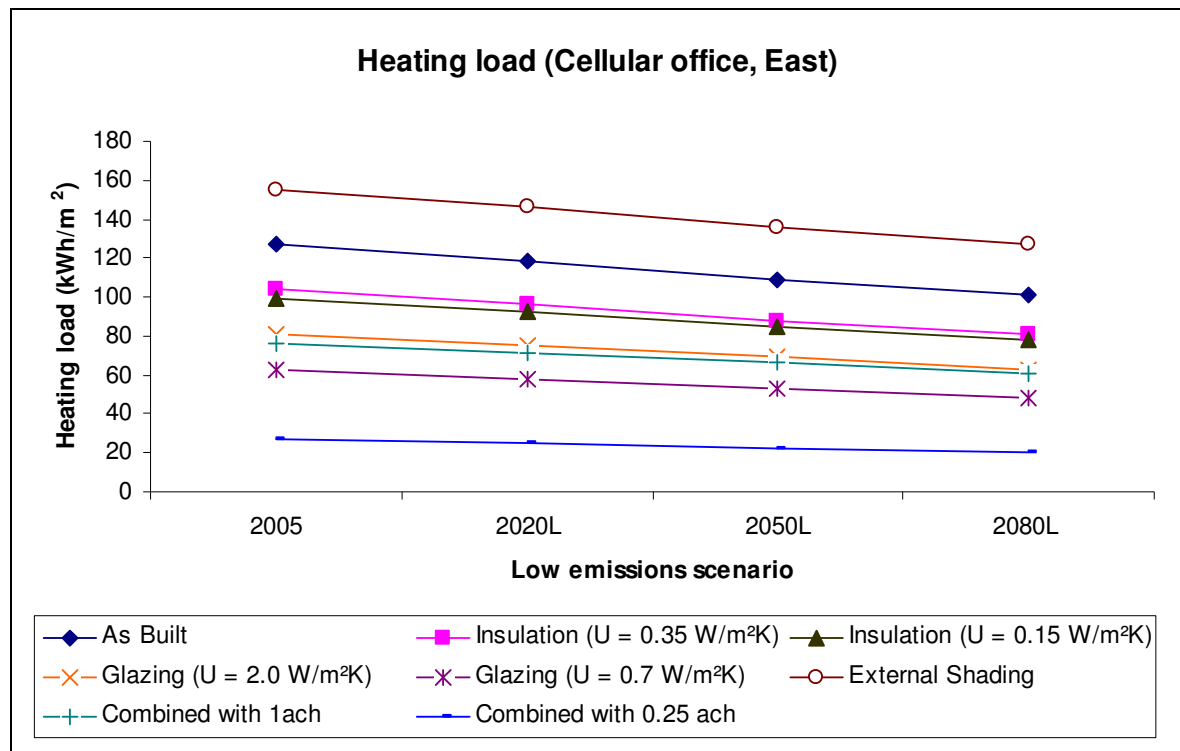
Figure 6.18 Heating loads under low and high emission scenarios for the east façade of the cellular office
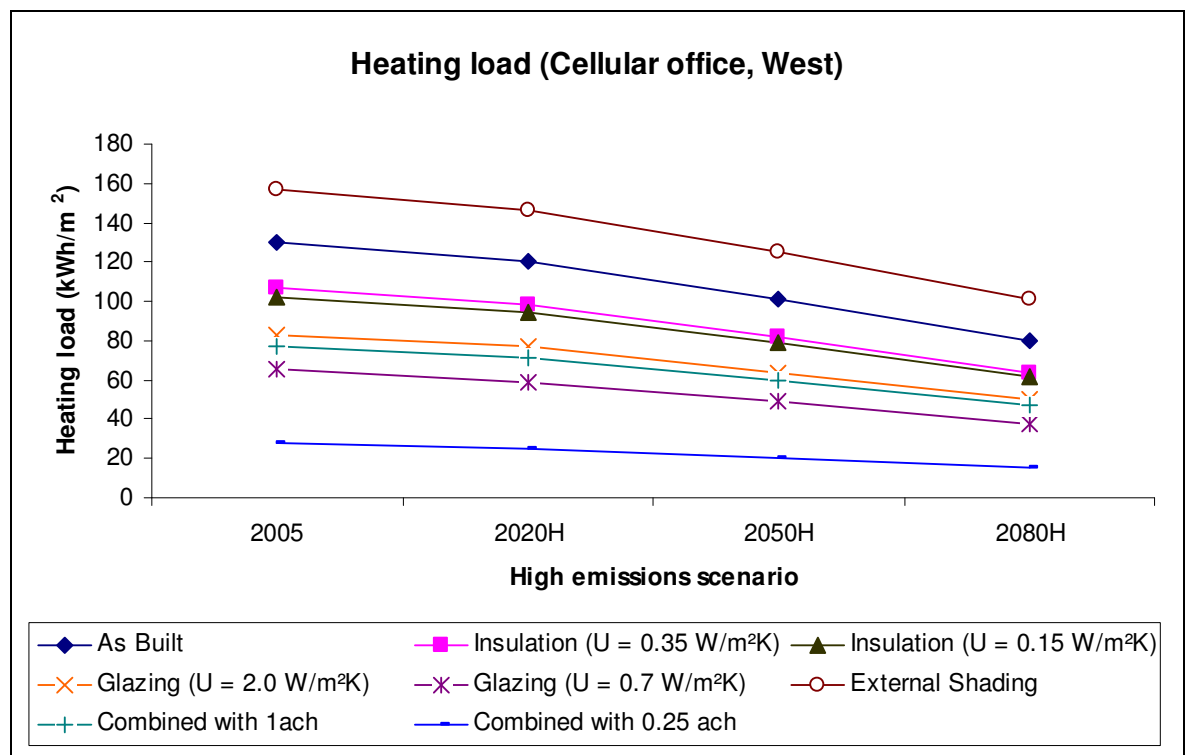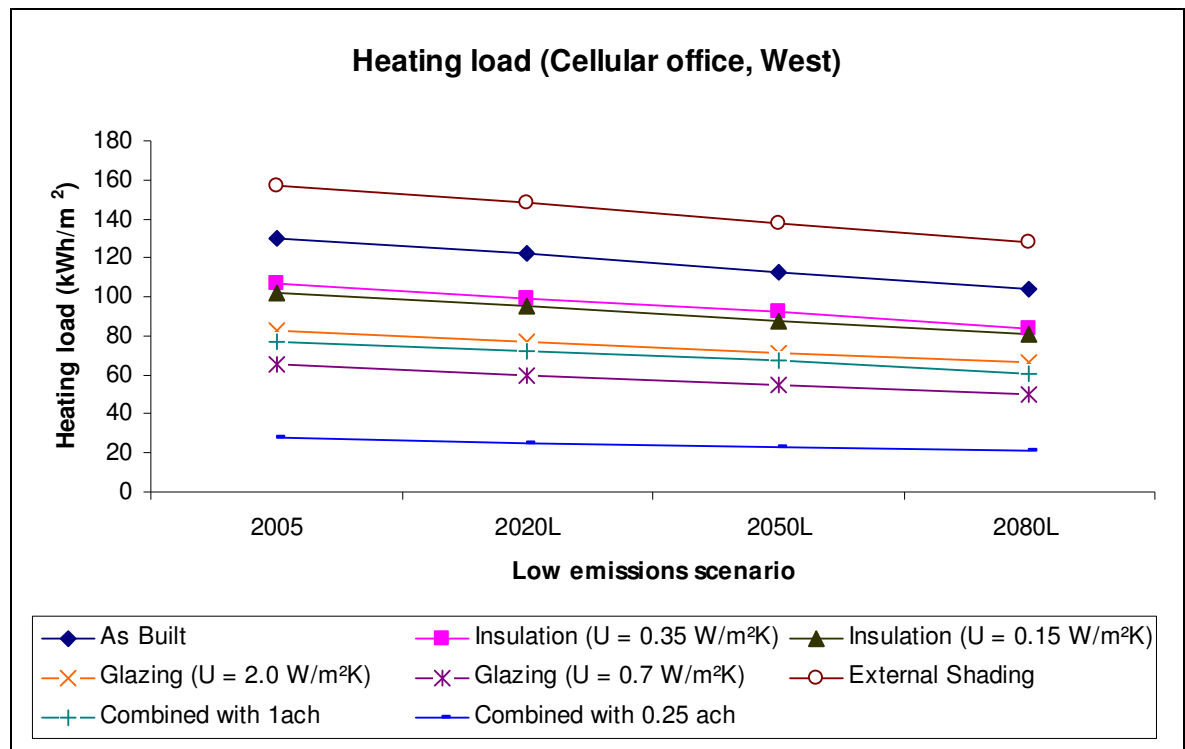
Figure 6.19 Heating loads under low and high emission scenarios for the west façade of the cellular office

External shading presents the worst single refurbishment solution in terms of heating demand. Applying external shading for the north orientation will increase the heating demand from 142 kWh/m^2 to 161 kWh/m^2 or 13 % of the as-built consumption in the present-day and from 90 kWh/m^2 to 105 kWh/m^2 or 17 % of the as-built consumption under the 2080s high emission (**Figure 6.16**). For the south orientation, the heating demand would increase from 106 kWh/m^2 to 148 kWh/m^2 or 40 % of the as-built consumption in the present-day and from 60 kWh/m^2 to 92 kWh/m^2 or 53 % of the as-built consumption under the 2080s high emission (**Figure 6.17**). Results for the other orientations fall within the range for the north and south façades.

'Combined all options with 0.25 ach' performs better than 'combined all options with 1 ach'. For the north orientation (**Figure 6.16**), 'combined all options with 0.25 ach' reduces the heating demand from 142 kWh/m^2 to 30 kWh/m^2 or 21 % of the as-built consumption in the present-day and from 90 kWh/m^2 to 17 kWh/m^2 or 19 % of the as-built consumption under the 2080s high emission compared with 80 kWh/m^2 or 56% of the as-built consumption and 50 kWh/m^2 or 56% of the as-built consumption respectively for 'combined all options with 1 ach'. For the south orientation (**Figure 6.17**), 'combined all options with 0.25 ach reduces the heating demand from 106 kWh/m^2 to 23 kWh/m^2 or 22 % of the as-built consumption in the present-day and from 60 kWh/m^2 to 11 kWh/m^2 or 18 % of the as-built consumption under the 2080s high emission compared with 71 kWh/m^2 or 67% of the as-built consumption and 41 kWh/m^2 or 68 % of the as-built consumption respectively for 'combined all options with 1 ach'. Results for the other orientations fall within the range for the north and south façades.

Heating load for open-plan office and teaching room are shown in **Appendix B**.

For the open plan office, using triple glazed windows presents the most effective single solution option while combined all options with 0.25 ach presents the most effective 'combined all' solution option (**Appendix B1**). However for the teaching room, adding 70 mm insulation and 12 mm plasterboard to the main layers of the wall (achieving U-value of 0.15 W/m^{2}K) presents the most effective single solution option (**Appendix B2**). Results show there is no need for heating using combined all with 0.25 ach as a 'combined all' solution for both present-day and under different climate change scenarios (**Appendix B2**). Similar to the cellular office, applying external shading in both the open-plan and teaching rooms presents the worst single solution since it results in more heating load compared to the as-built option (**Appendix B1 and B2**).

6.10.4 Cooling Load

Figures 6.20-6.23 present the predicted cooling loads in the cellular office under low and high emissions scenarios and for different refurbishment options using Birmingham TRY weather files. As expected, the cooling load is increased significantly as a result of climate change. While the north orientation has the highest heating demand, it presents the lowest cooling demand with 3 kWh/m^2 in the as built state (**Figure 6.20**). The east (**Figure 6.22**) and west orientations (**Figure 6.23**) show similar behaviour with 7 kWh/m^2 while the south orientation (**Figure 6.21**) is slightly lower with 6 kWh/m^2. Generally, the cooling demand for both the east and west orientations is similar to the south orientation while the heating demand is significantly higher.
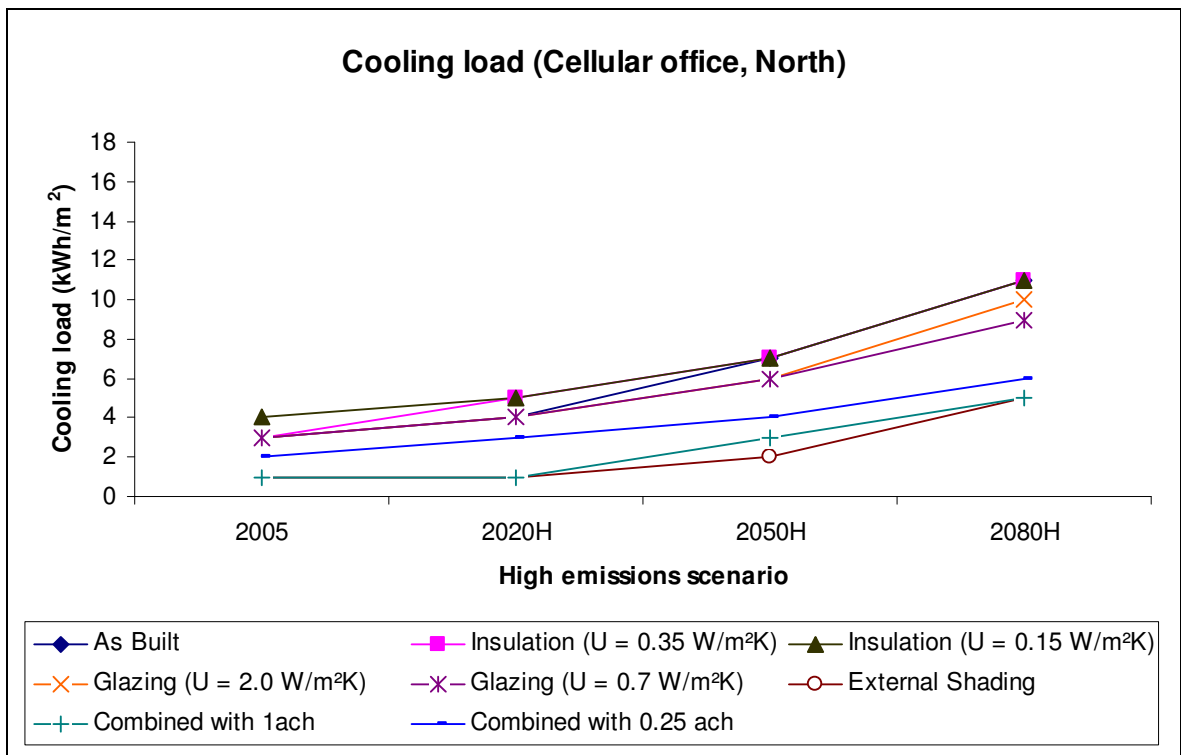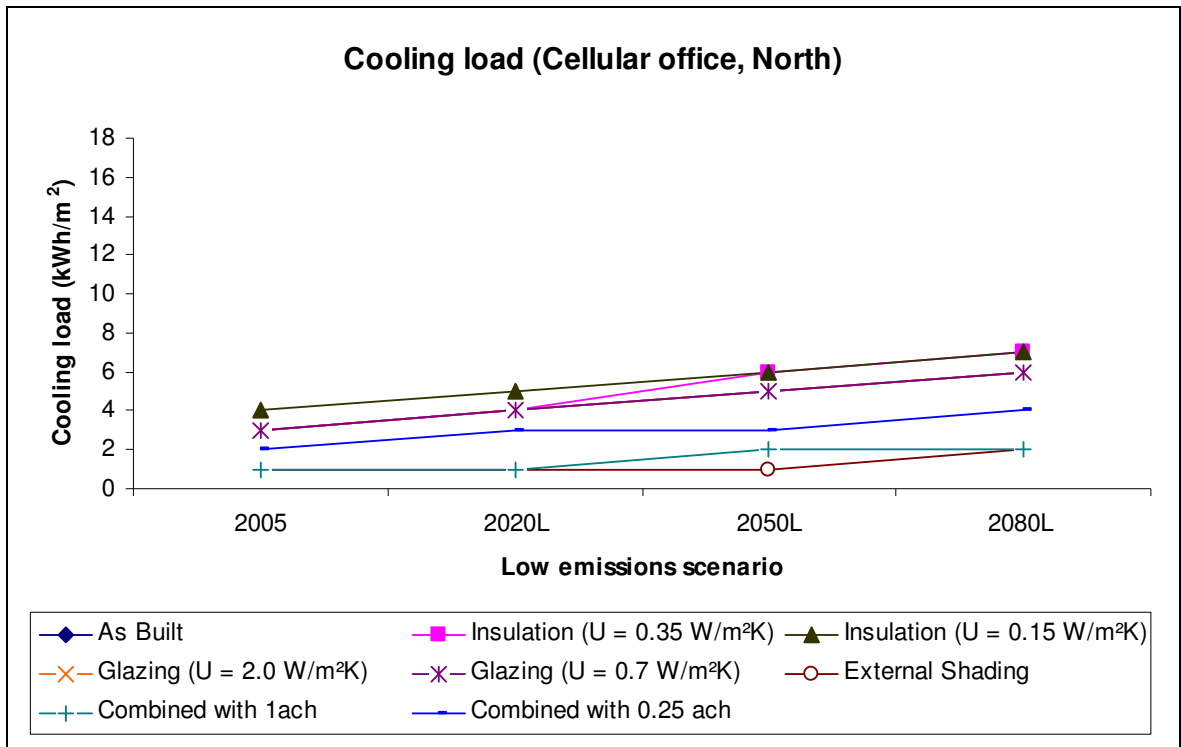
Figure 6.20 Cooling loads under low and high emission scenarios for the north façade of the cellular office
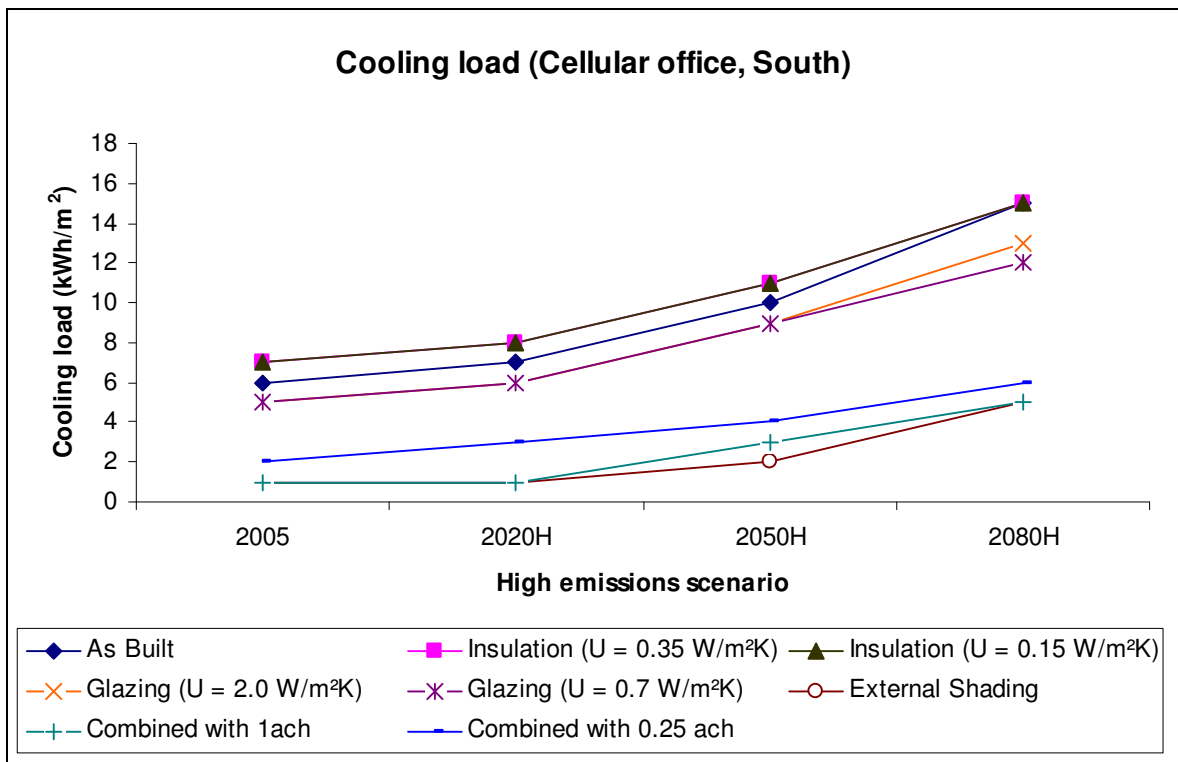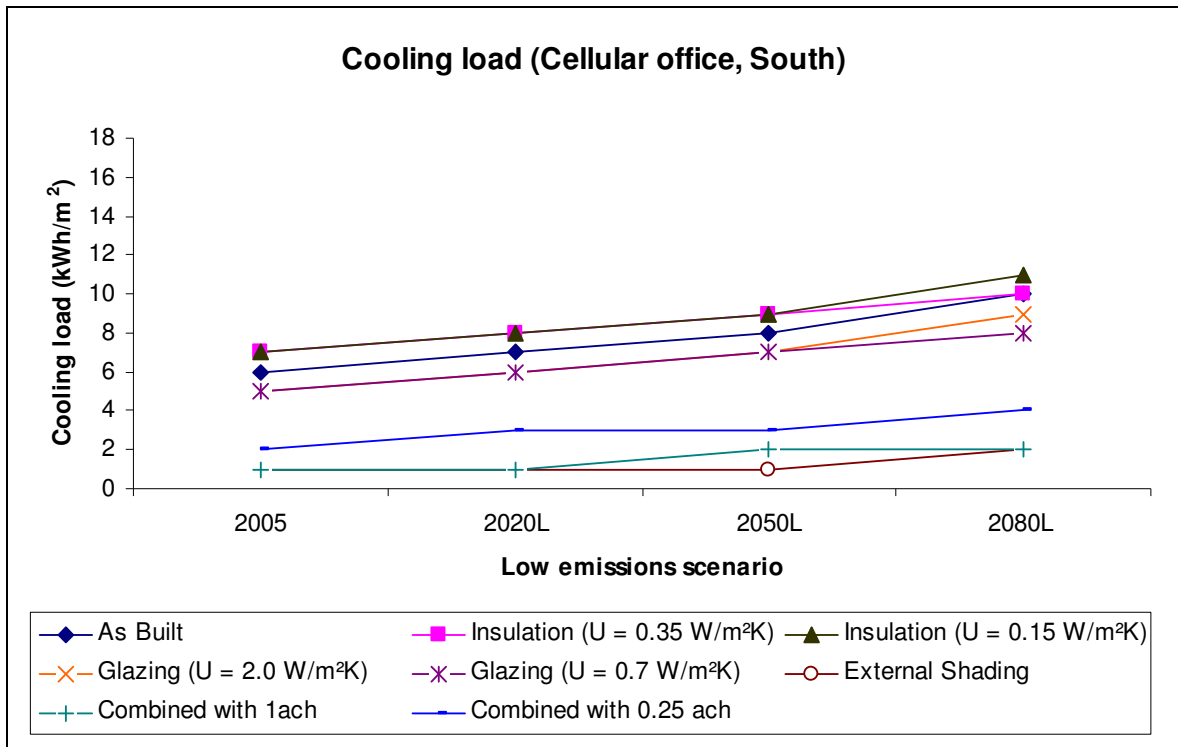
Figure 6.21 Cooling loads under low and high emission scenarios for the south façade of the cellular office
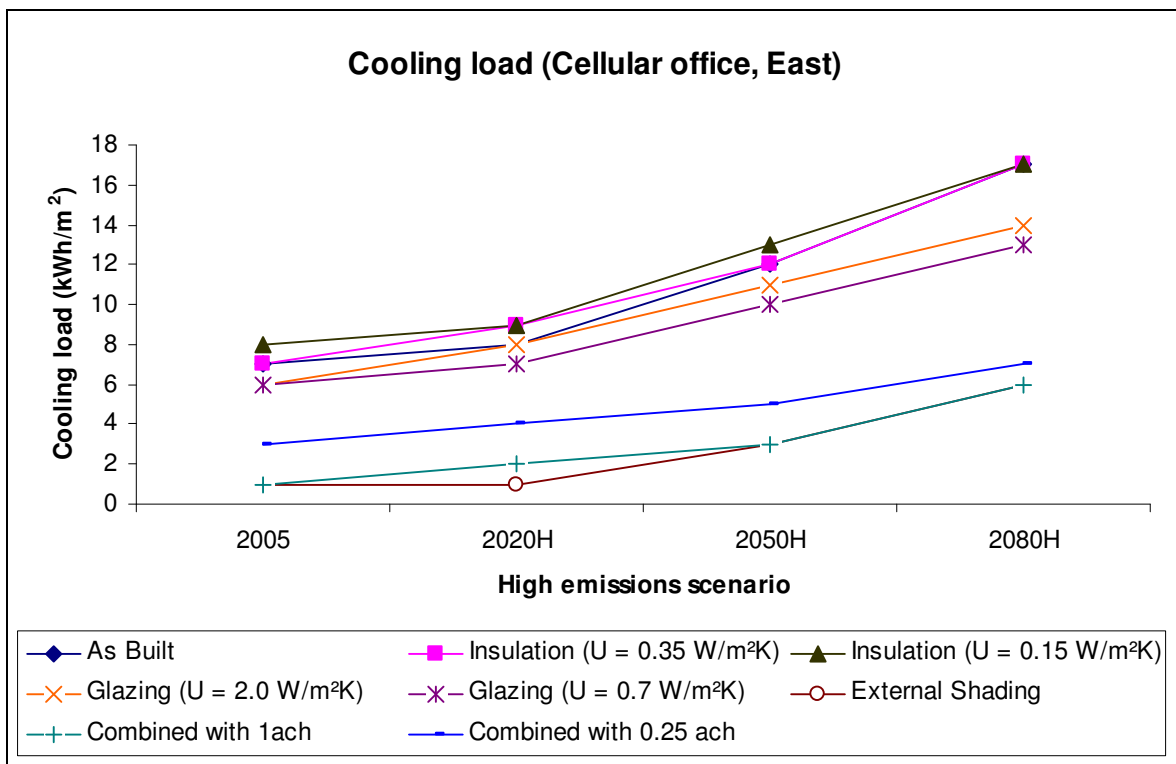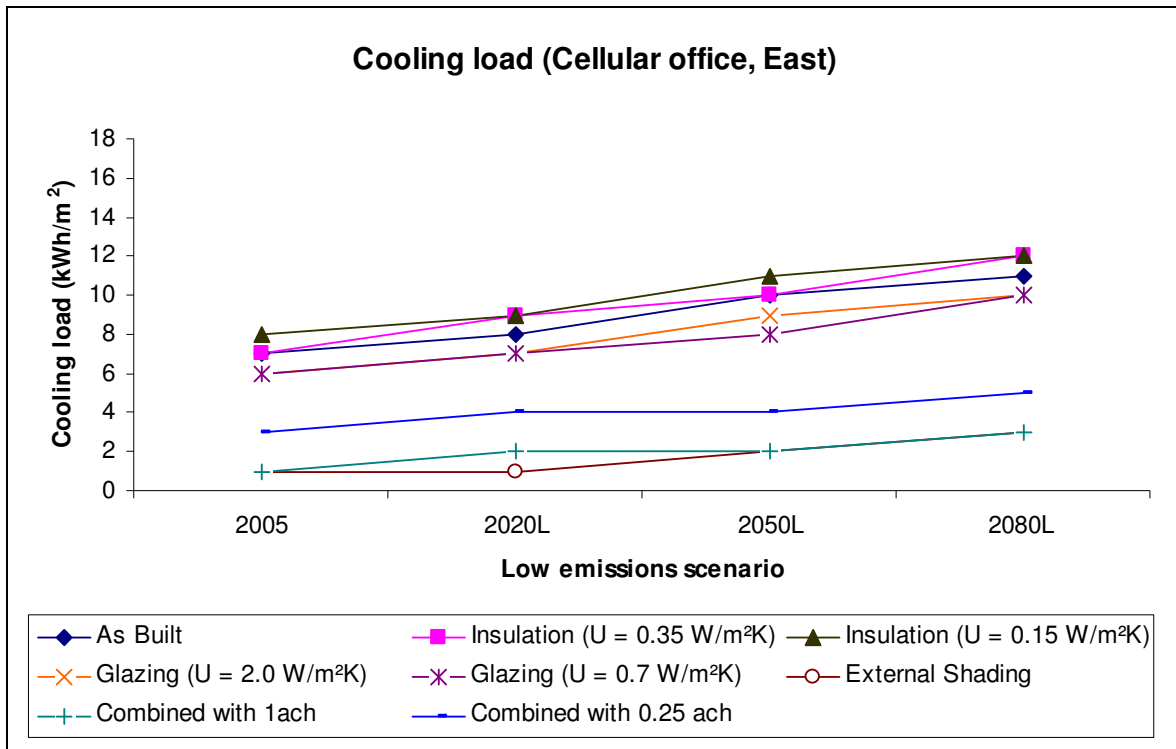
Figure 6.22 Cooling loads under low and high emission scenarios for the east façade of the cellular office
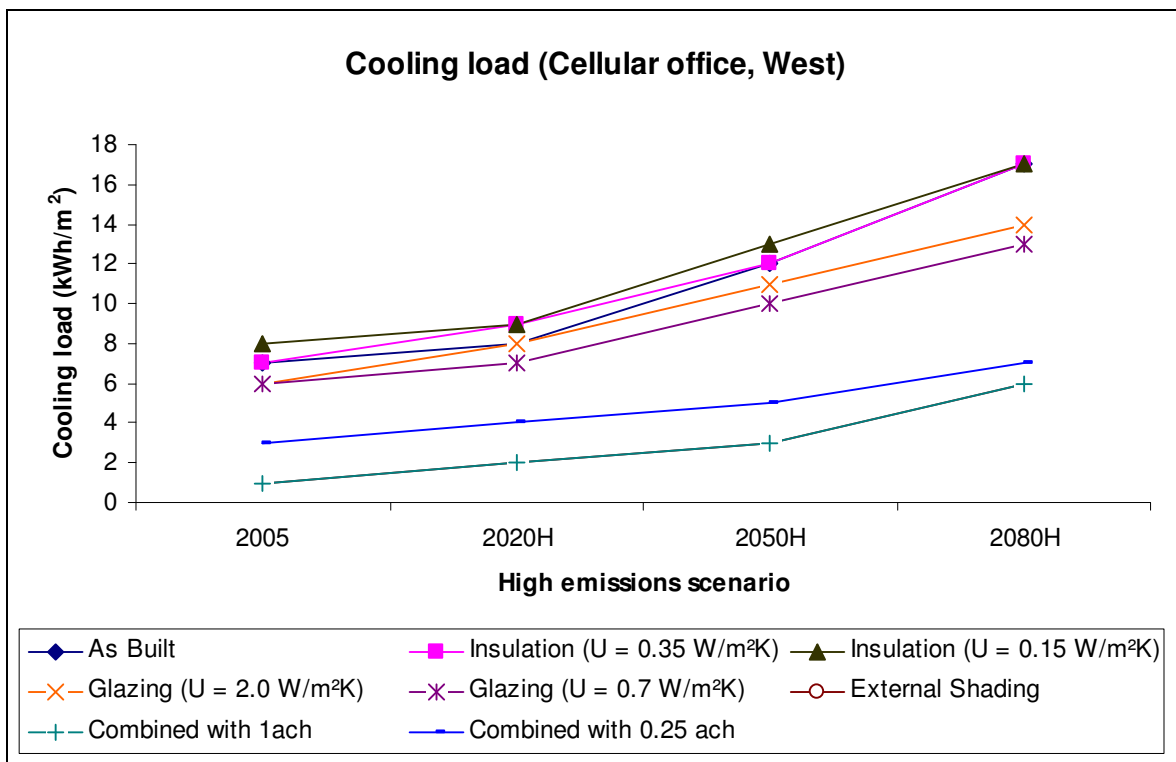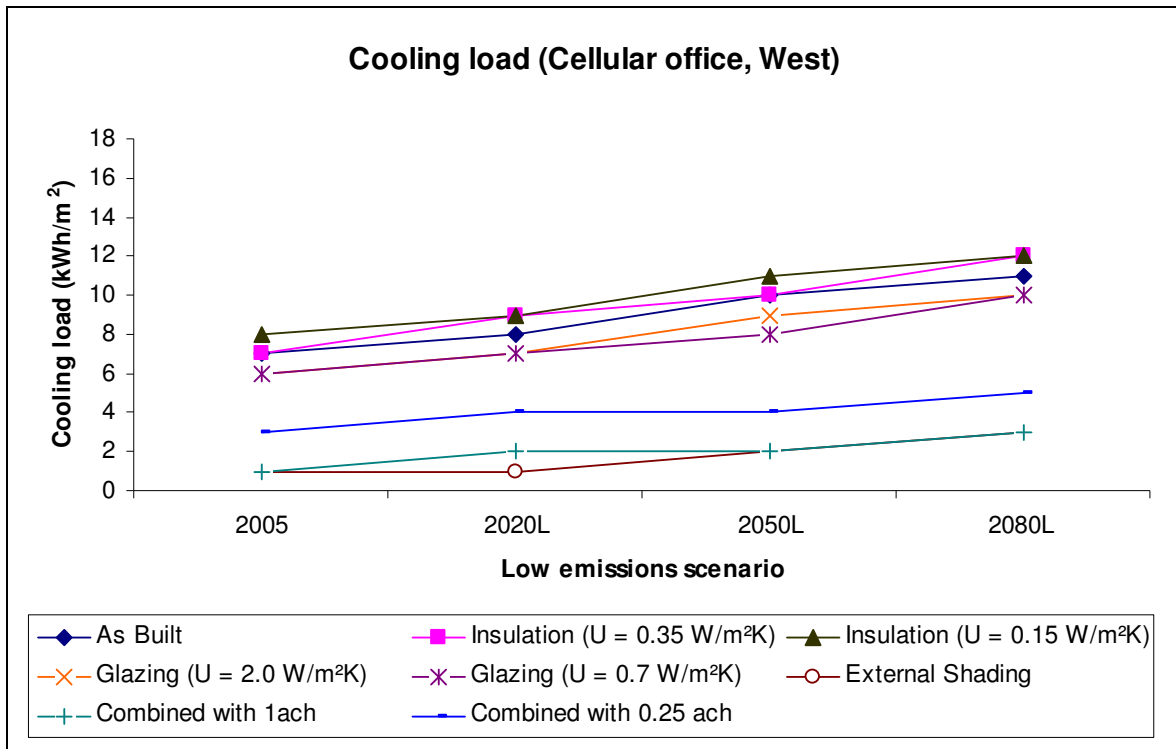
Figure 6.23 Cooling loads under low and high emission scenarios for the west façade of the cellular office

When looking for a single solution for reducing cooling energy demand, applying external shading gives the best result. For the north façade, the cooling demand is reduced from 3 kWh/m^2 to 1 kWh/m^2 or to 33 % of the as-built consumption in the present-day and from 11 kWh/m^2 to 5 kWh/m^2 or to 45 % of the as-built consumption under the high emission scenario in the 2080s timeslice (**Figure 6.20**). For the east façade, the cooling demand is reduced from 7 kWh/m^2 to 1 kWh/m^2 or to 14 % of the as-built consumption and from 17 kWh/m^2 to 6 kWh/m^2 or to 35 % of the as-built consumption under the high emission scenario in the 2080s timeslice (**Figure 6.22**). Results for the other orientations fall within the range for the north and east façades.

This single solution is more effective than using a 'combination of all solutions with 0.25 ach' (as used successfully for the heating loads) which only reduces the cooling demand from 3 kWh/m^2 to 2 kWh/m^2 or to 67 % of the as-built consumption in the present-day and from 11 kWh/m^2 to 6 kWh/m^2 or to 55 % of the as-built consumption under the high emission scenario in the 2080s timeslice for the north façade (**Figure 6.20**). For the east façade, the cooling demand is reduced from 7 kWh/m^2 to 3 kWh/m^2 or to 43 % of the as-built consumption in the present-day and from 17 kWh/m^2 to 7 kWh/m^2 or to 41 % of the as-built consumption under the high emission scenario in the 2080s (**Figure 6.22**). Results for the other orientations fall within the range for the north and east façades.

Adding 70 mm insulation and 12 mm plasterboard to the main layers of the wall (achieving U-value of 0.15 W/m^{2}K) presents the worst single refurbishment solution in terms of cooling demand. For the north orientation, improving the wall insulation (achieving U-value of 0.15 W/m^{2}K) will increase the cooling demand from 3 kWh/m^2 to 4 kWh/m^2 or 133 % of the as-built consumption in the present-day and from 10 kWh/m^2 to 11 kWh/m^2 or to 110 % of the

as-built consumption under the 2080s high emission scenario (**Figure 6.20**). For the east orientation, the cooling demand would increase from 7 kWh/m^2 to 8 kWh/m^2 or to 114 % of the as-built consumption in the present-day and from 16 kWh/m^2 to 17 kWh/m^2 or to 106 % of the as-built consumption under the 2080s high emission scenario (**Figure 6.22**). Results for the other orientations fall within the range for the north and east façades.

Cooling loads for open-plan office and teaching room are shown in **Appendix C**. For the open plan office (**Appendix C1**) and the teaching room (**Appendix C2**) and for different orientations, using external shading presents the most effective single solution option while 'combined all options with 1 ach' performs better than combined all options with 0.25 ach. It is worth noting that for the teaching room, 'combined all with 0.25 ach' option presents the worst solution since it will result in a significant increase in the cooling demand compared to the as built under the present day and for different climate change scenarios.

6.10.5 Total Energy Demand and The Associated CO$_2$ Emissions

Figures 6.24-6.27 present the predicted total energy demands in cellular office under low and high emission scenarios and for different refurbishment options. These figures were generated from adding the heating and cooling load together. **Figures 6.28-6.31** present the total CO$_2$ emissions. Total CO$_2$ emissions were calculated based on an assumed mix of fuel types (0.194 kg CO$_2$/kWh for heating loads and 0.422 for cooling loads). Total energy demands for open plan and teaching room are shown in **Appendix D** while the associated total CO$_2$ emissions for them are shown in and **Appendix E**.

a) Total Energy Demand
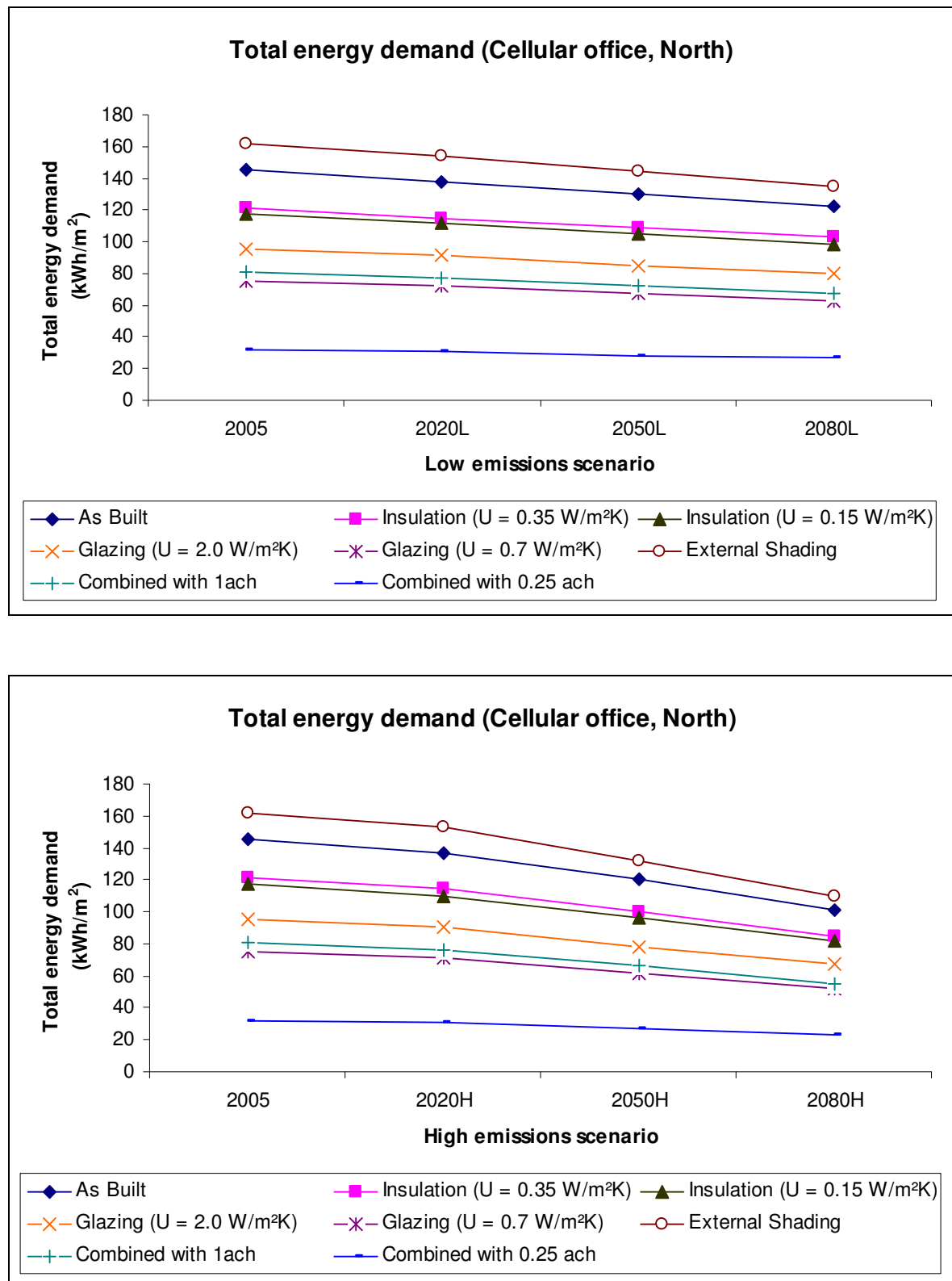
Figure 6.24 Total energy demand under low and high emission scenarios for the north façade of the cellular office
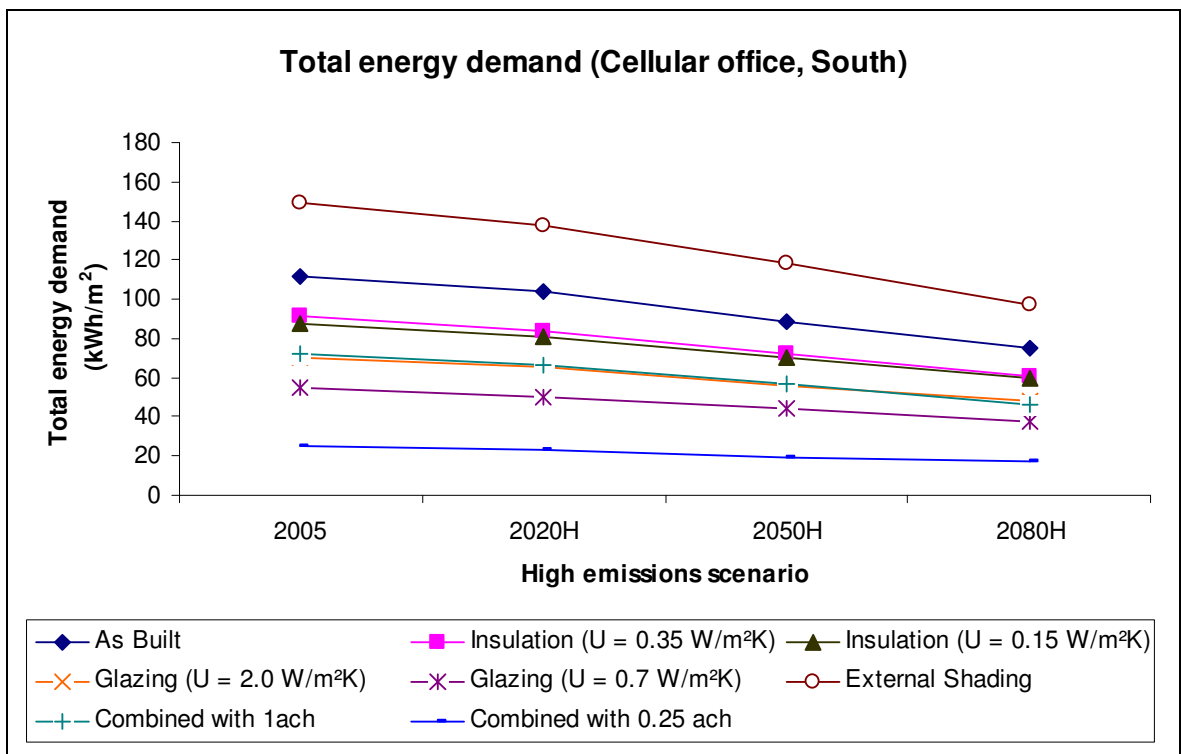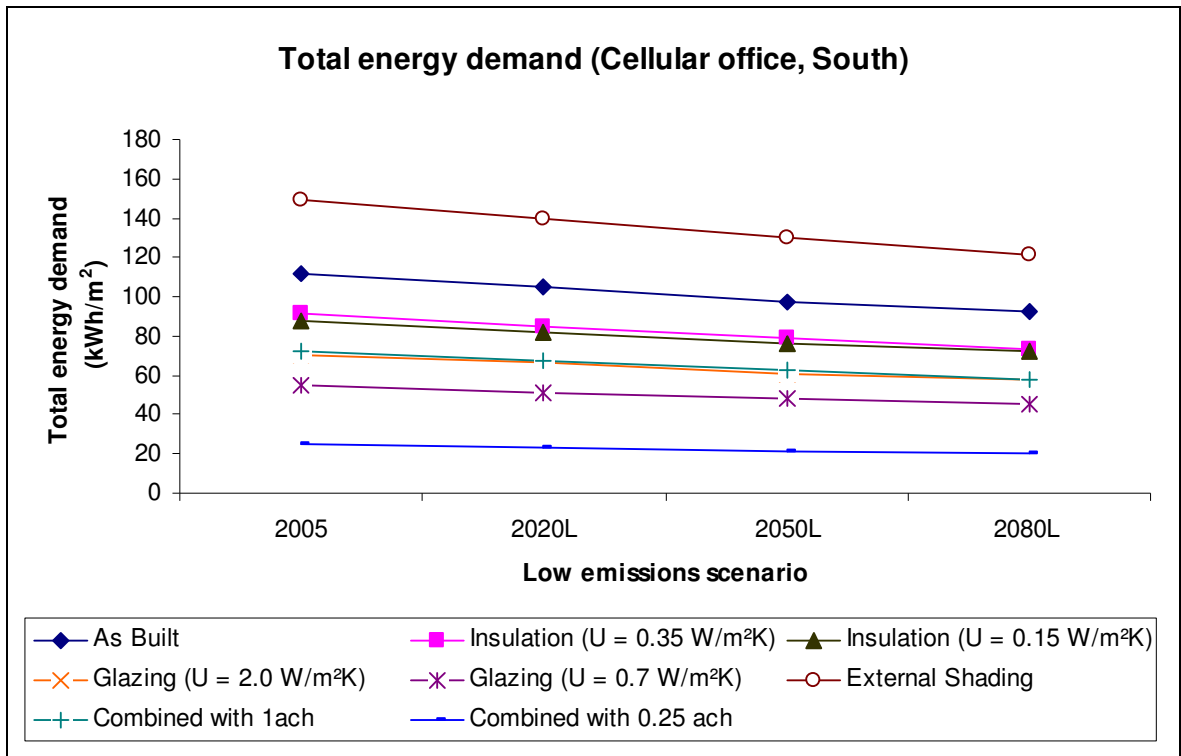
Figure 6.25 Total energy demand under low and high emission scenarios for the south façade of the cellular office
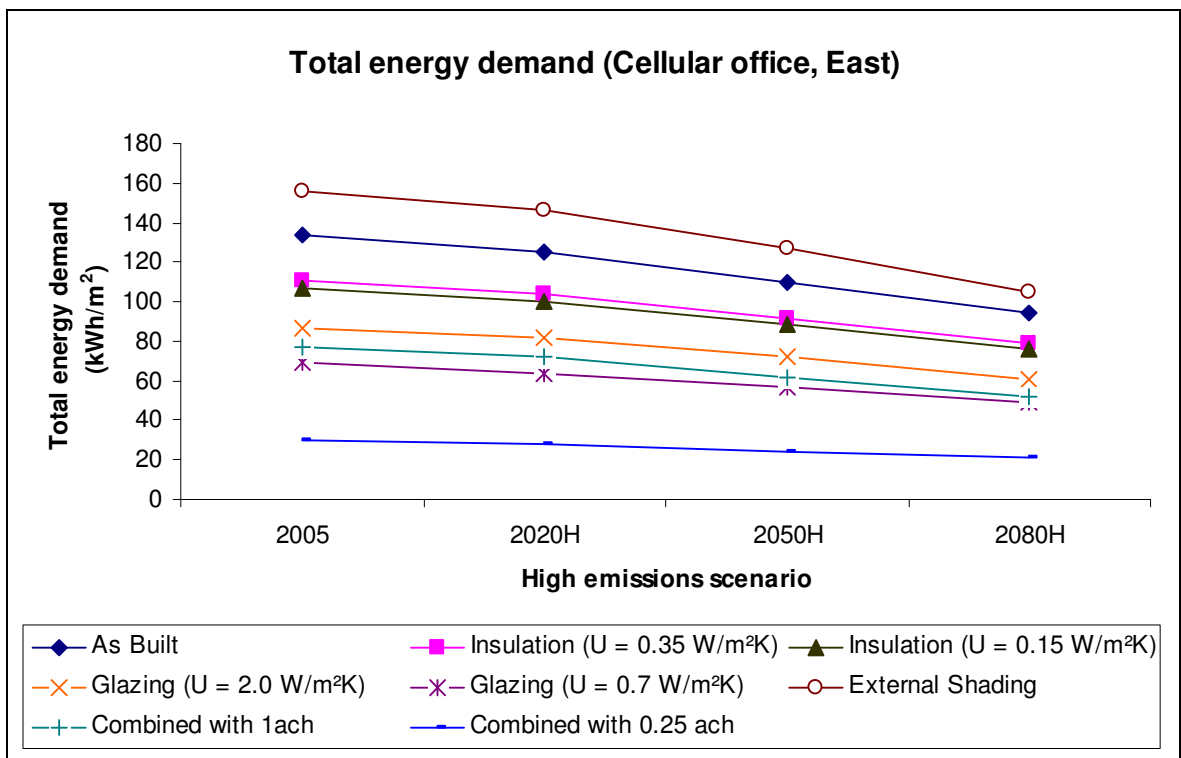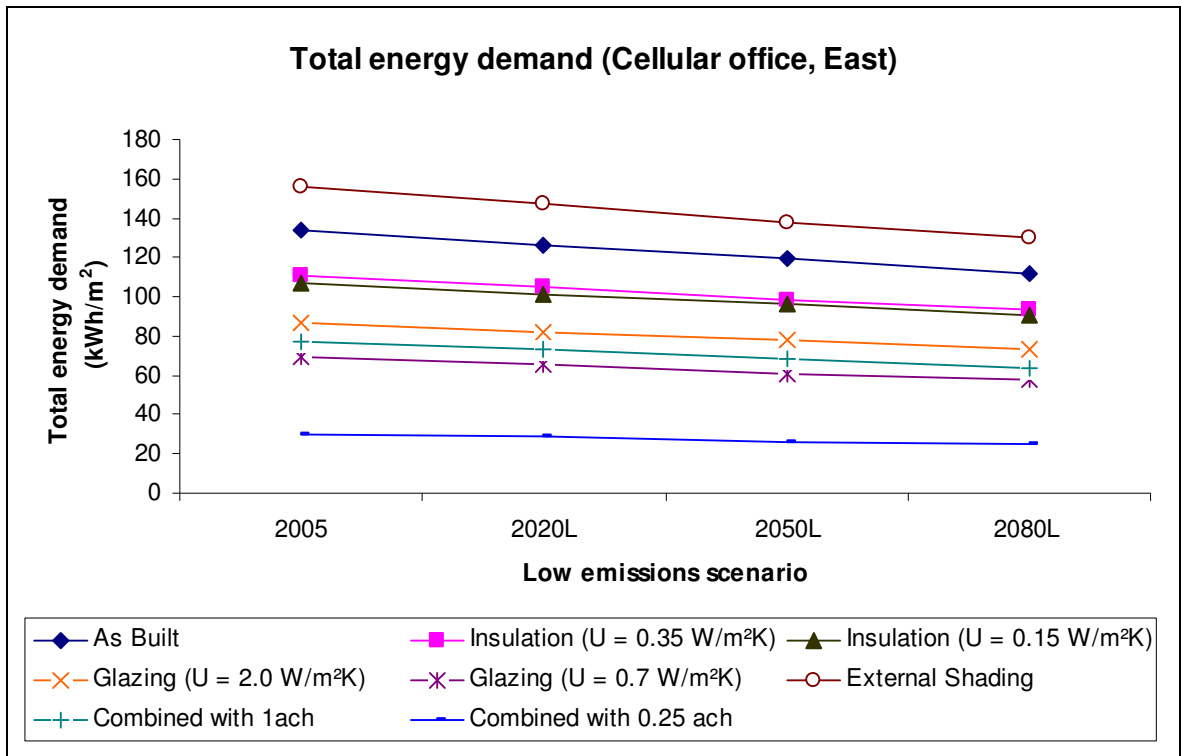
Figure 6.26 Total energy demand under low and high emission scenarios for the east façade of the cellular office

Total energy demand (Cellular office, West)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total energy demand (Cellular office, West)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach
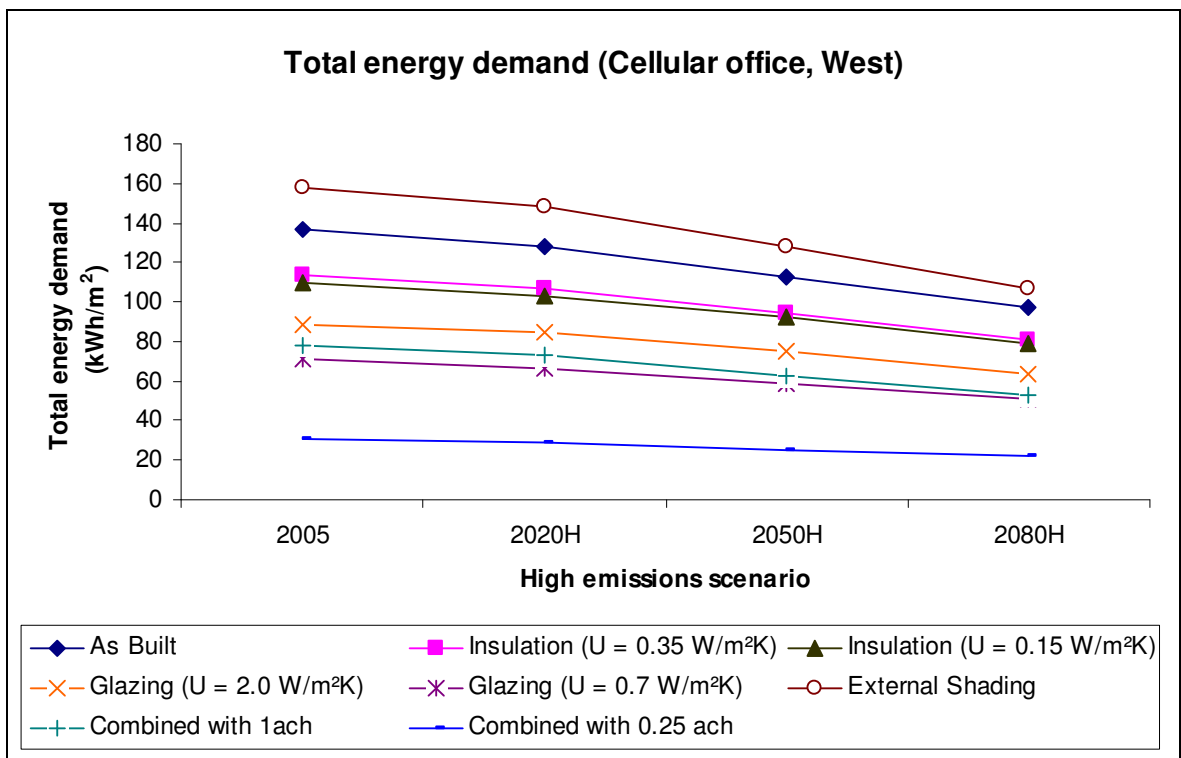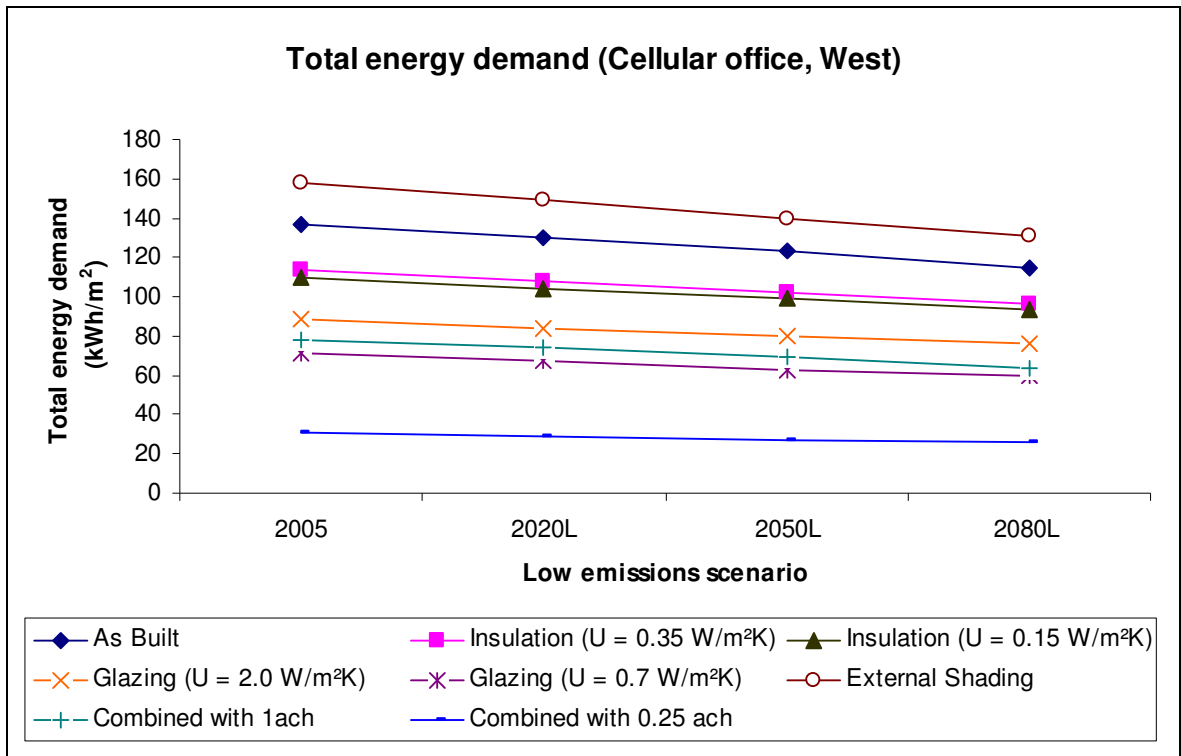
Figure 6.27 Total energy demand under low and high emission scenarios for the west façade of the cellular office

b) Total CO₂
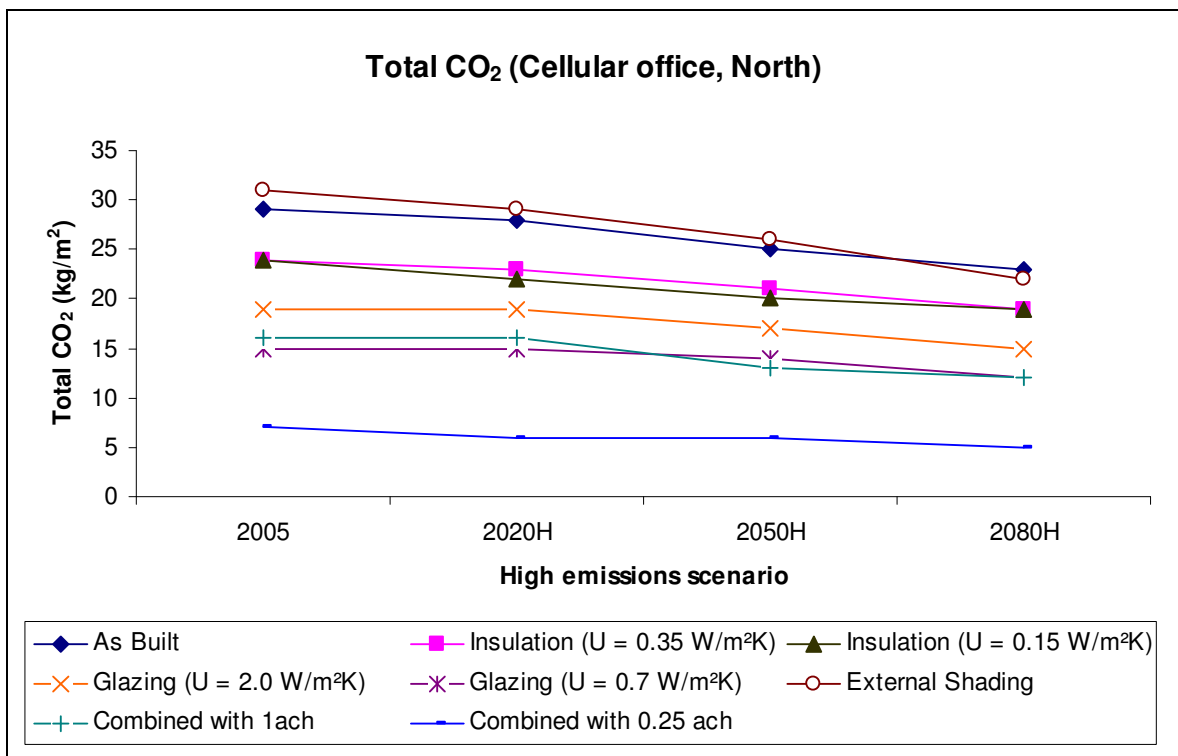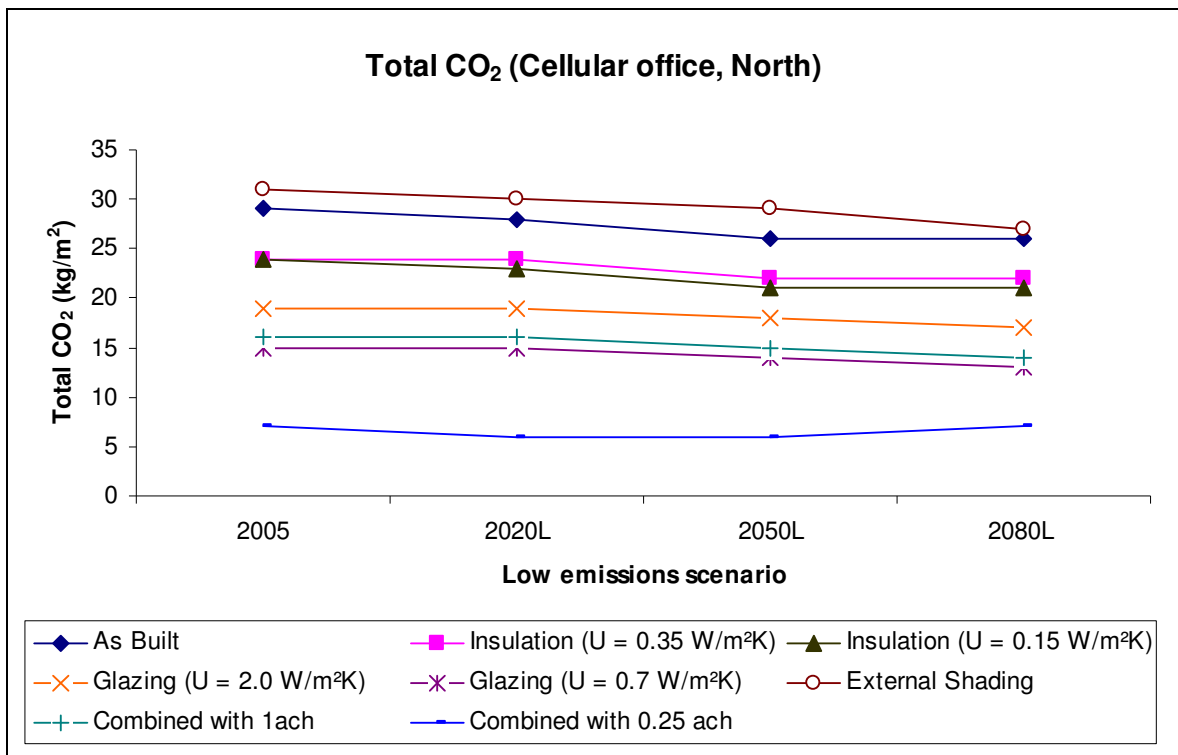
Figure 6.28 Total CO_2 emissions under low and high emission scenarios for the north façade of the cellular office

Total CO_2 (Cellular office, South)

[Chart: Total CO_2 (kg/m²) vs Low emissions scenario (2005, 2020L, 2050L, 2080L)]

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO_2 (Cellular office, South)

[Chart: Total CO_2 (kg/m²) vs High emissions scenario (2005, 2020H, 2050H, 2080H)]

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Figure 6.29 Total CO_2 emissions under low and high emission scenarios for the south façade of the cellular office

Total CO$_2$ (Cellular office, East)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO$_2$ (Cellular office, East)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach
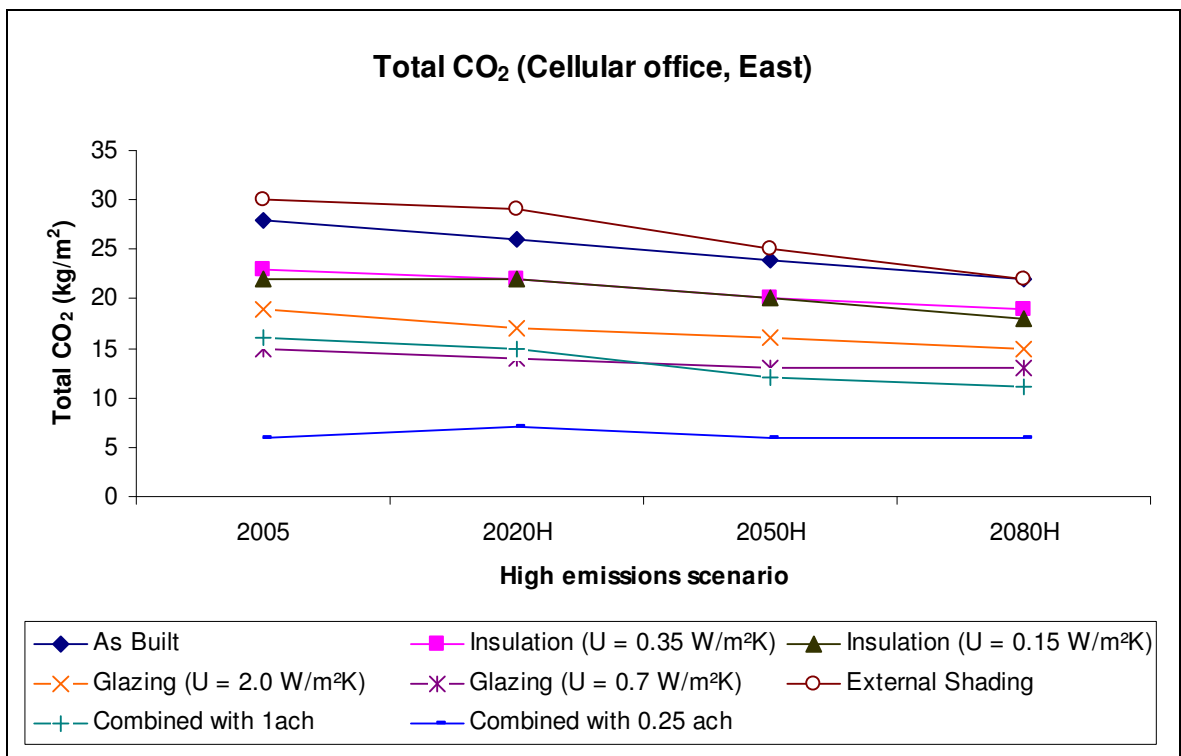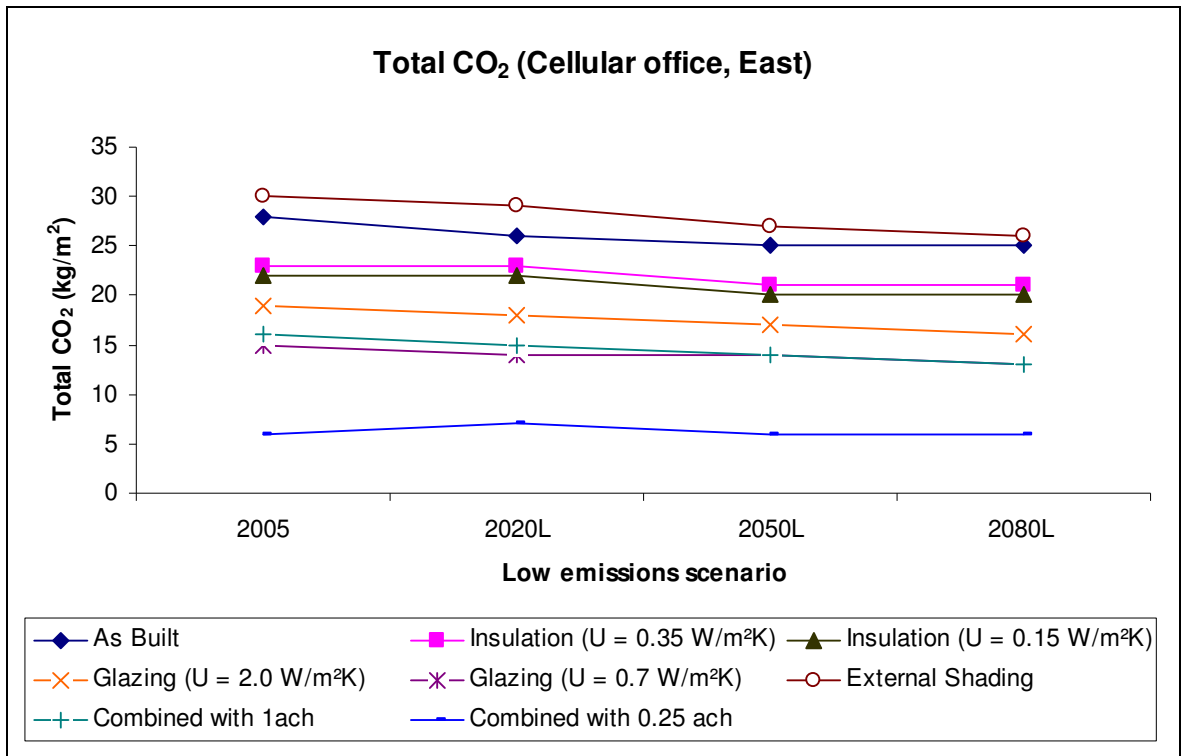
Figure 6.30 Total CO$_2$ emissions under low and high emission scenarios for the east façade of the cellular office

Total CO₂ (Cellular office, West) — Low emissions scenario

Total CO₂ (Cellular office, West) — High emissions scenario
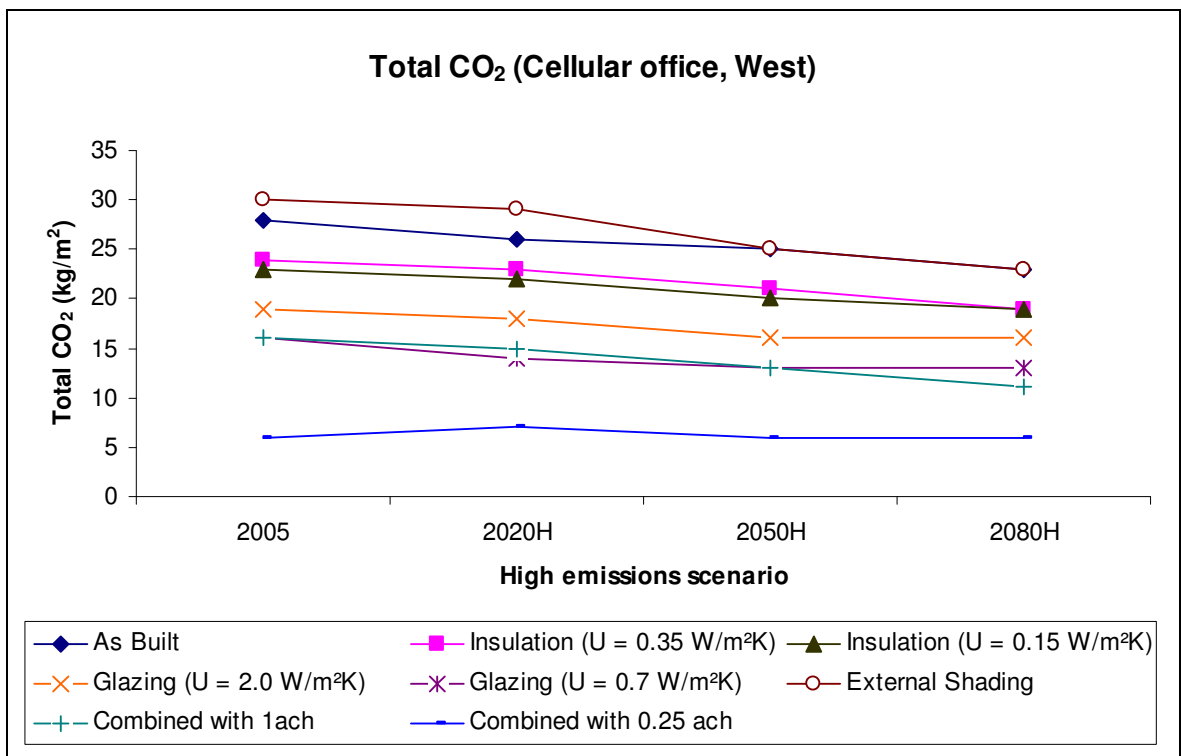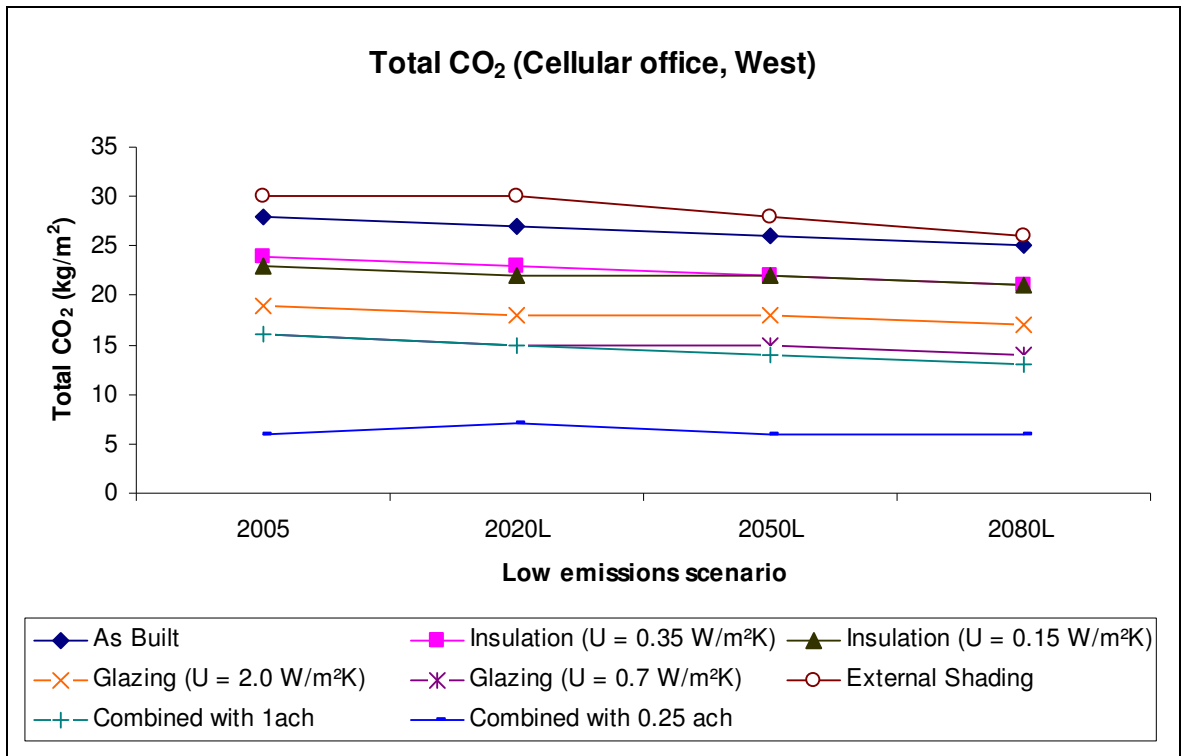
Figure 6.31 Total CO$_2$ emissions under low and high emission scenarios for the west façade of the cellular office

Unlike most of the other results (e.g. heating loads, cooling loads and total energy demands) total CO_2 emission results do not display a linear response with time because the intensity of CO_2 emissions for heating energy and cooling energy are different. For example, for different orientations, total CO_2 emissions from using 'combined all with 1 ach' option does not show linear response with time and can be observed clearly under the high emission scenario for different timeslices (**Figures 6.28-6.31**).

Replacing single glazed windows with triple one (U-value = 0.7 W/m^{2}K) presents the best single solution in terms of relative total energy demands and CO_2 emissions for both cellular office (**Figure 24-31**) and open-plan office (**Appendix D1 and E1**). However, for teaching room improving (**Appendix D2 and E2**) wall insulation to achieve U-value of 0.15 W/m^{2}K present the best single solution. External shading presents the worst single refurbishment solution and results in significant increase in total energy demands and CO_2 emissions compared to the as-built state for all rooms and under different climate change scenarios.

'Combined all with 0.25 ach' option performs better than 'combined all with 1 ach' in terms of annual total energy demands and CO_2 emissions for the present-day and for different climate change scenarios.

CHAPTER SEVEN

DISCUSSION OF THE RESULTS

7.1   Introduction

The overarching aim of this research is to investigate how climate change will affect the social, economic and environmental aspects of refurbishment strategies applied to post-war HE buildings in the UK. In this chapter, the results that were generated from the IES simulation programme are analysed and their significance is discussed.

7.2   As-Built Thermal Comfort

Results from the thermal analysis (**Figure 6.9-6.11**) suggest that for most rooms in Muirhead Tower, the levels of overheating are not acceptable under present day conditions and this effect will increase over time. Increases occur across all three room types at all orientations (**Figure 6.9-6.11**). However, there is a substantial difference in the level to which the temperature threshold is exceeded. Open plan and lecture room performance is worse than for a cellular office. The poor performance of those rooms is likely to be due to the poor standard of the building envelope, the higher density of occupants and equipment together with limited ventilation provision and lack of ventilation control.

These rooms have a relatively greater sensitivity to the indoor environment due to internal loads than cellular offices. Consequently, discomfort temperatures are less associated with the external temperatures in these rooms than they are for cellular offices and more likely to be a consequence of internal gains. However, it is clear that given the potential magnitude of these increases in internal temperatures, refurbishment strategies designed to improve overheating performance under present day conditions might not be effective in the future. For example, refurbishment options designed to cater for worst-case conditions (high emissions scenario) might needlessly consume resources if that scenario does not develop. Conversely, options designed to cater for best-case conditions (low emissions scenario) might not be effective in the future.

Mechanical cooling might be seen as an obvious solution to guarantee thermal comfort during hotter summers. However, this solution is undesirable since it will increase the energy demand and may compromise greenhouse gas reduction targets (e.g. cooling is often delivered using electricity with its high CO_2 emissions). Therefore, there is a need to reduce cooling loads as far as possible using passive and low energy-methods and supply any residual cooling requirements in the most efficient manner. Each of these methods needs to be considered systematically and their relative performance under different climate scenarios evaluated to ensure they are effective in the future.

The results also (**Figure 6.9-6.11**) highlight the sensitivity of performance under low and high emission scenarios for different timeslices. For the 2020 timeslice, while the number of hours above 28°C under low and high emission scenarios is approximately the same for different rooms and orientations, there is a slight difference in the number of hours in 2050s,

increasing further to a considerable difference in 2080s. This raises the question of the sensitivity of different refurbishment options to future uncertain changes.

Currently the likelihood of different future climates emerging is unknown, although UKCIP09 may help to address this issue (Jenkins et al., 2009) therefore, it is imperative that the adaptability and flexibility of refurbishment solutions are also considered. This will enable managers and designers to ensure that any given building system can be adjusted or modified in line with prevailing climate conditions as they become clearer in the future and help ensure that long-term performance and sustainability is maintained.

7.3   Refurbishment Options Performance

The performance of each refurbishment option in the present day conditions and under different climate change scenarios for different orientations is shown in (**Figures 6.12-6.15**) for cellular office. Results for both open-plan office and teaching room are shown in **Appendix A**. Clearly when existing previously poorly insulated rooms become well-insulated (e.g. wall insulation and windows replacement), the number of hours with temperature above limit during occupation time is increasing significantly for all orientations. These findings can be explained by the fact that solar energy gains and internal heat gains are much less transmitted through the well-insulated envelope than through the poorly insulated one.

It is worth noting that heat from outside is also transmitted less to the inside. However, for heat gains, thermal transmittance is much less relevant as compared to internal gains. Thus heat is accumulated during periods of hot spells. Energy loss through the façade depends particularly on internal and external temperatures and is independent of orientation while solar energy gain is clearly orientation sensitive.

External shading system performs the best as a single refurbishment solution, in terms of thermal comfort level provided, compared to the other single or combined solutions, since it blocks out the Sun's rays and prevents the ingress of direct solar radiation during the summer but permits it during the winter. Solar radiation can be reflected and absorbed by the external shading. However a disadvantage of this system is that it results in some permanent loss of passive solar gain and useful daylight when needed for both heating and lighting (**Figure 7.1**). Moreover, it blocks a significant amount of diffuse radiation (i.e. radiation that reaches a surface from all directions) (Tzempelikos and Athienitis, 2007).
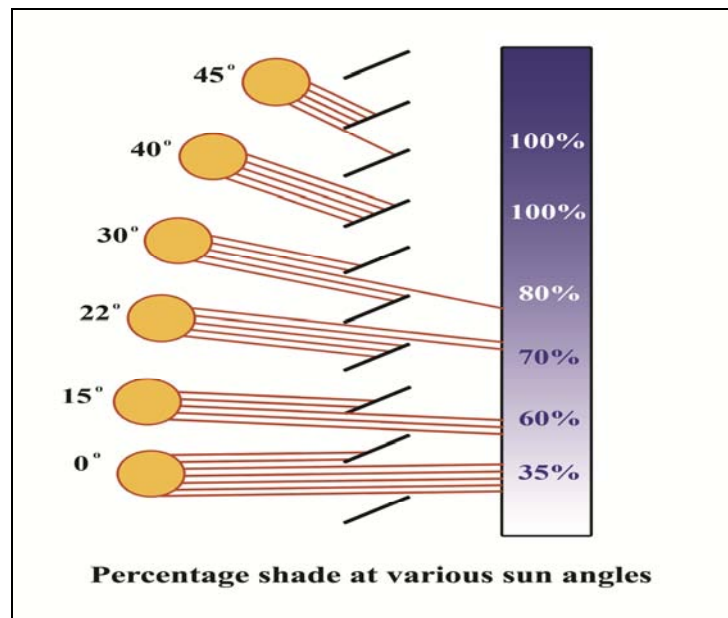
Figure 7.1 Koolshade system
Source: (Koolshade, 2009)

External shading can ensure thermal comfort in the cellular office room until 2050s while for the open-plan and the teaching rooms the overheating threshold of 28°C is only guaranteed within the acceptable limit under the present-day condition. This is partly due to high internal gains from occupants and equipment in those rooms.

As the outside temperature further increases as a result of climate change, the reliance on external shading to prevent direct solar gains will not be enough and excessive overheating is likely to occur. The only way to provide comfort will be to use mixed mode ventilation (i.e. combining natural ventilation with mechanical cooling) to provide the required remaining cooling (Hacker et al., 2005). The mixed-mode strategy depends on a well-designed natural ventilation system most of the time with mechanical cooling only provided when and where the natural ventilation fails to deliver the required levels of comfort on its own (CIBSE, 2004).

In the cellular office room, windows replacement performs better (i.e. less number of hours above 28°C) than wall insulation for different orientations (**Figure 6.12-6.15**). This shows that during the summer, the balance between solar gains and thermal losses is slightly in favour of the high performance windows. For the teaching room, the same would occur partly due lower glazing ratio (10 % of the total façade area) which results in less solar gain (**Appendix A2**). However, for the open-plan office (**Appendix A1**) the opposite will happen (i.e. wall insulation performs better with less number of hours above 28°C compared with high performance windows) due to a higher glazing ratio (55 % of the total façade area).

Therefore, the balance between solar gains and thermal losses is in favour of the wall insulation for the open-plan office. Results also show the significant impact of reducing air infiltration on the comfort level. Well insulated airtight rooms with 0.25 ach shows increased level of overheating compared to 1 ach for the present-day and for all future climate change scenarios. This impact can be seen clearly in the open-plan office and the teaching room where there is a higher density of occupation and equipment compared to the cellular office.

Night cooling (i.e. using natural ventilation combined with thermal mass to cool the surfaces of the building fabric at night) can be seen as a solution to significantly reduce overheating impacts (Hacker et al., 2008). This approach is more effective where buildings include a high thermal mass, so that heat can be absorbed during the day (Hacker et al., 2008). However, overheating cannot be completely excluded for days of high external ambient temperature. This indicates that at a certain air change level no further benefits can be expected as the building has reached temperatures close to the outside ambient. Moreover, the security consideration at night may prevent any efficient utilisation of night cooling opening windows except for rooms on upper floors.

The impacts of night cooling and changing air infiltration are beyond the scope of this work for the reasons previously discussed in **Chapter 5** (**Section 5.6.2**). However, since the university summer term time is likely to end in June, and the teaching rooms are likely to be unoccupied after that date this will help to avoid days with temperatures above comfort level within these kinds of rooms. This shows that how rooms are utilised is another factor that should be taken into account.

7.4   Heating and Cooling Load

Results from the thermal analysis (**Figures 6.16-6.23** for the cellular office, **Appendix B and C** for the open-plan and the teaching rooms) highlight the sensitivity of different orientations and refurbishment options to heating loads, cooling loads and alternative climate scenarios. In the UK, the north orientation has the highest heating demand and the lowest cooling demand due to limited solar gain throughout the year (CIBSE, 2006; Szokolay, 2008). During winter seasons, the south orientation has higher solar incident than other orientations and therefore less heating energy is required. East and west orientations show similar behaviour, although the cooling demand is slightly higher for the east. In general, the cooling demand for both east and west is similar to south while the heating demand is significantly higher.

Figures 7.2-7.5 present savings in heating energy demand for different refurbishment options for the cellular office while the results for open-plan and teaching room are shown in **Appendix F**. In terms of savings of space heating energy relative to the 'as built', triple glazed windows with a U-value of 0.7 W/m^{2}K used as a single solution in both cellular (**Figure 7.2-7.5**) and open-plan (**Appendix F1**) delivers the largest savings in energy demand.
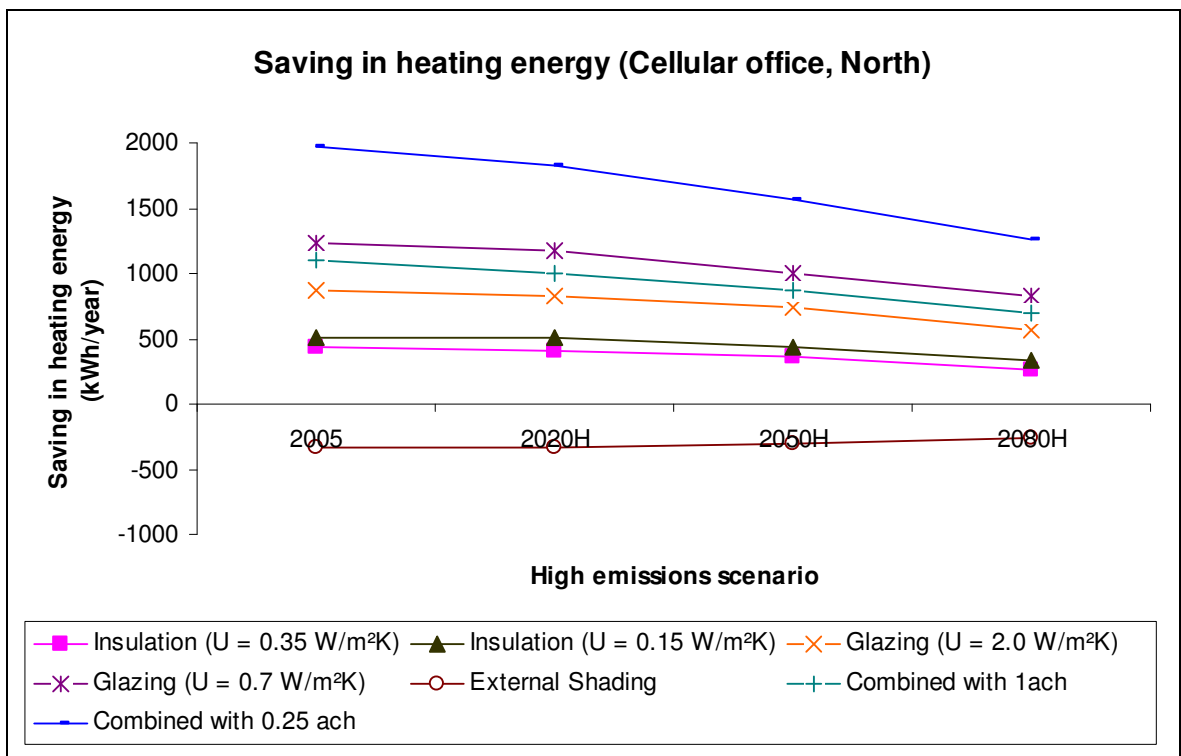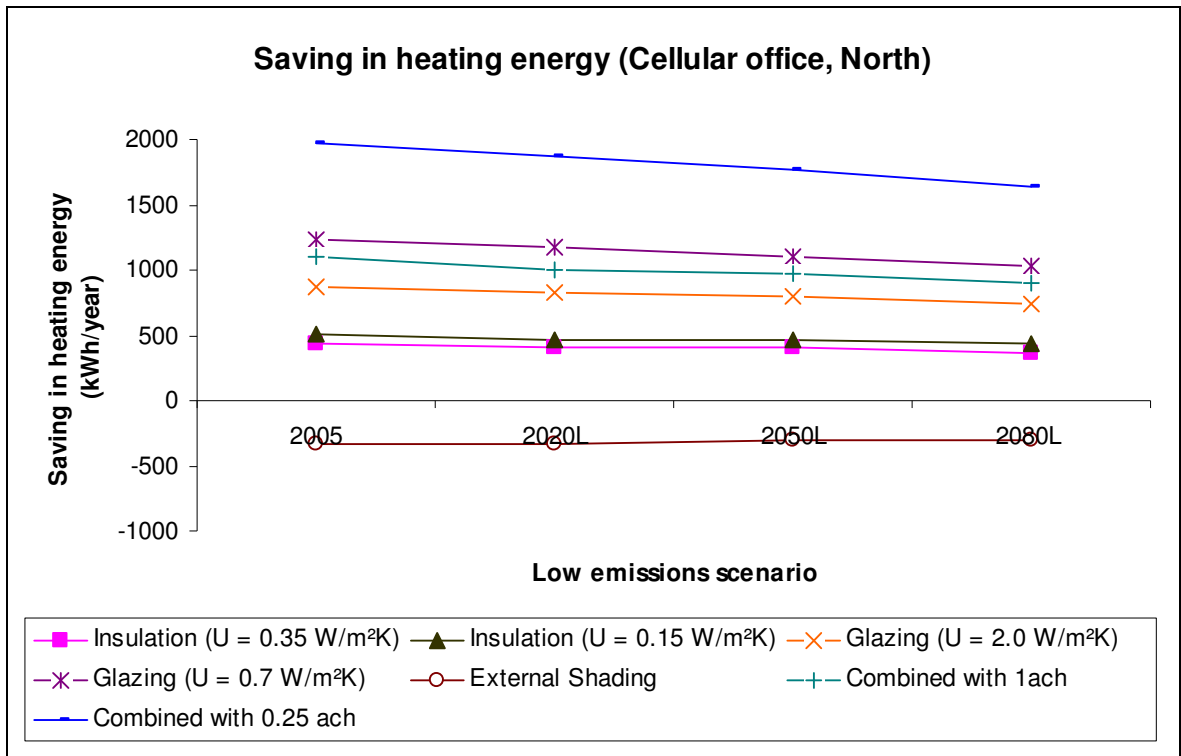
Figure 7.2 Saving in heating energy demand under different climate scenarios for the north façade of the cellular office
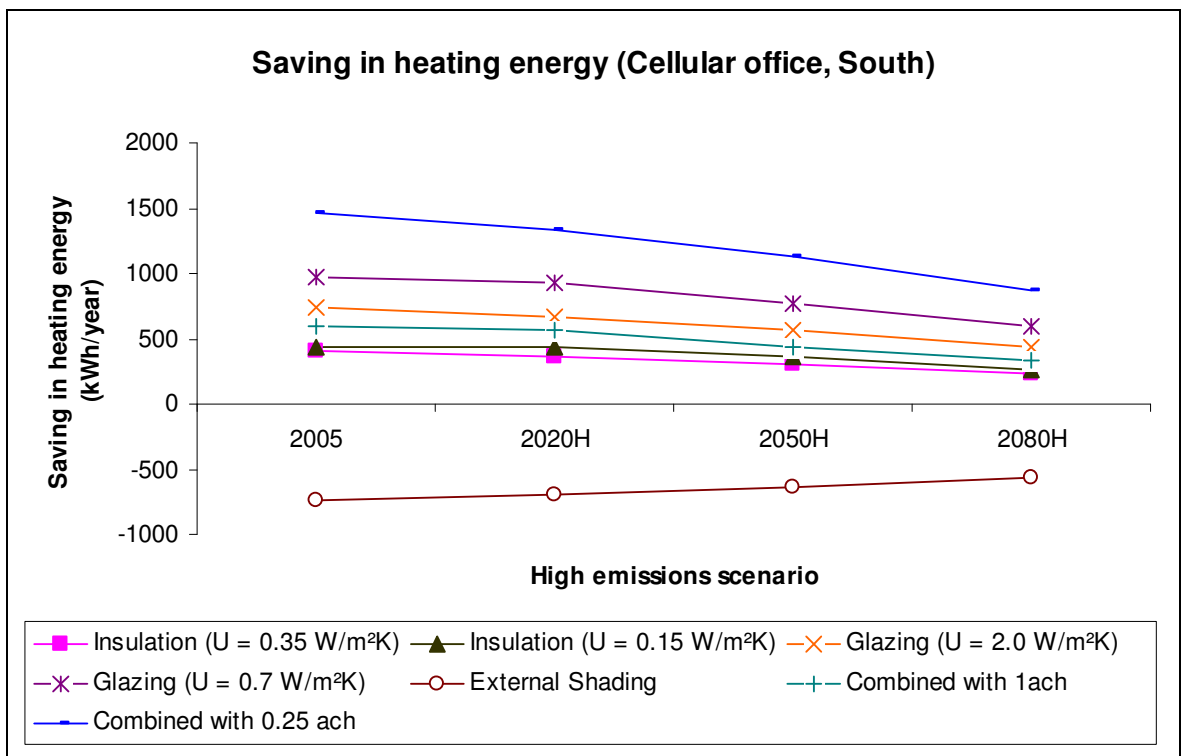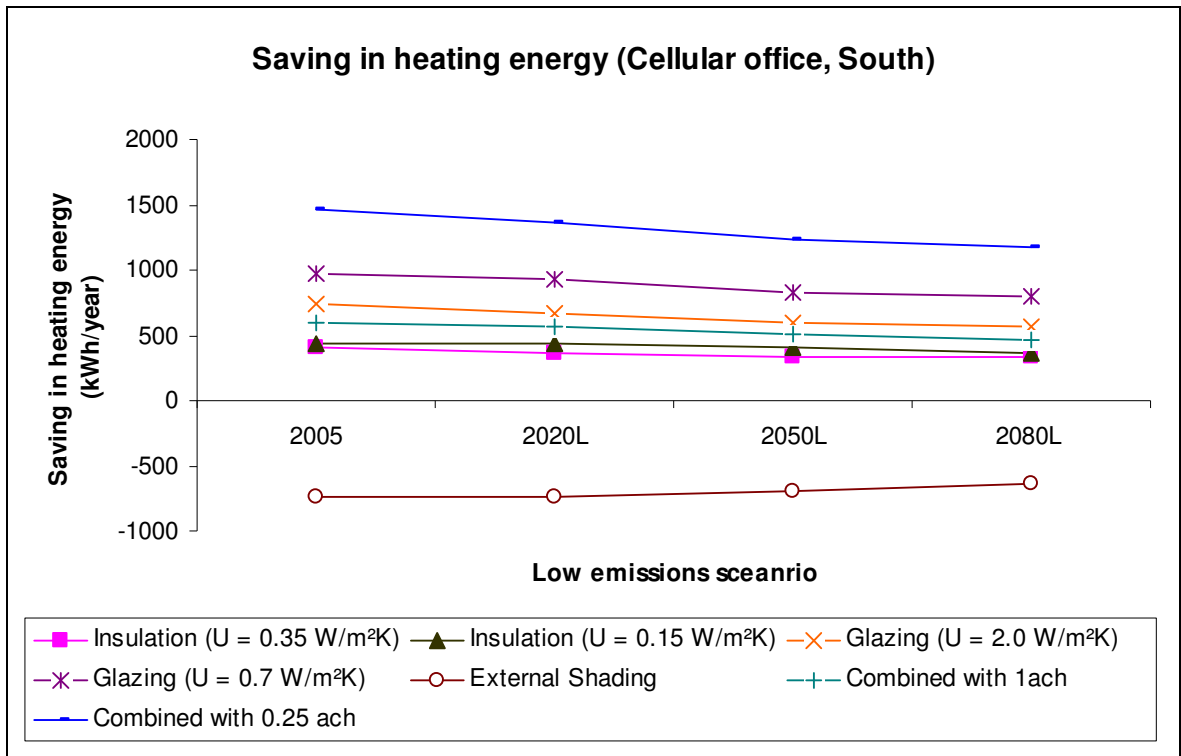
Figure 7.3 Saving in heating energy demand under different climate scenarios for the south façade of the cellular office
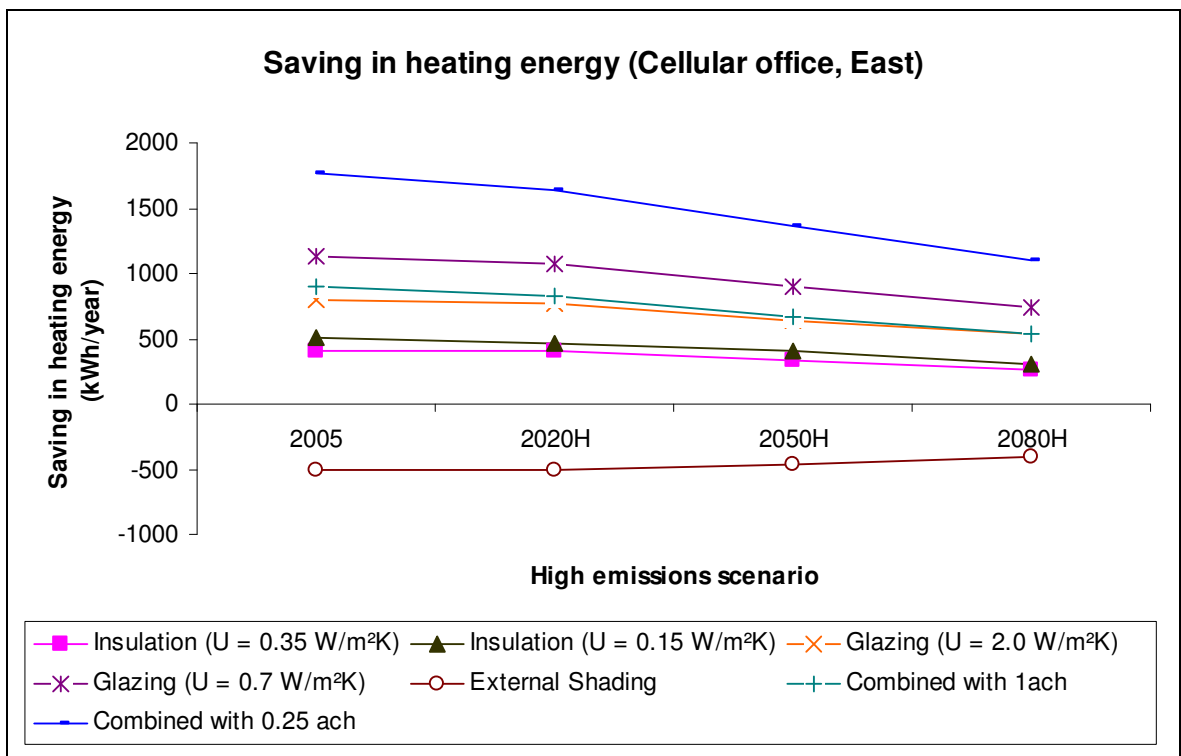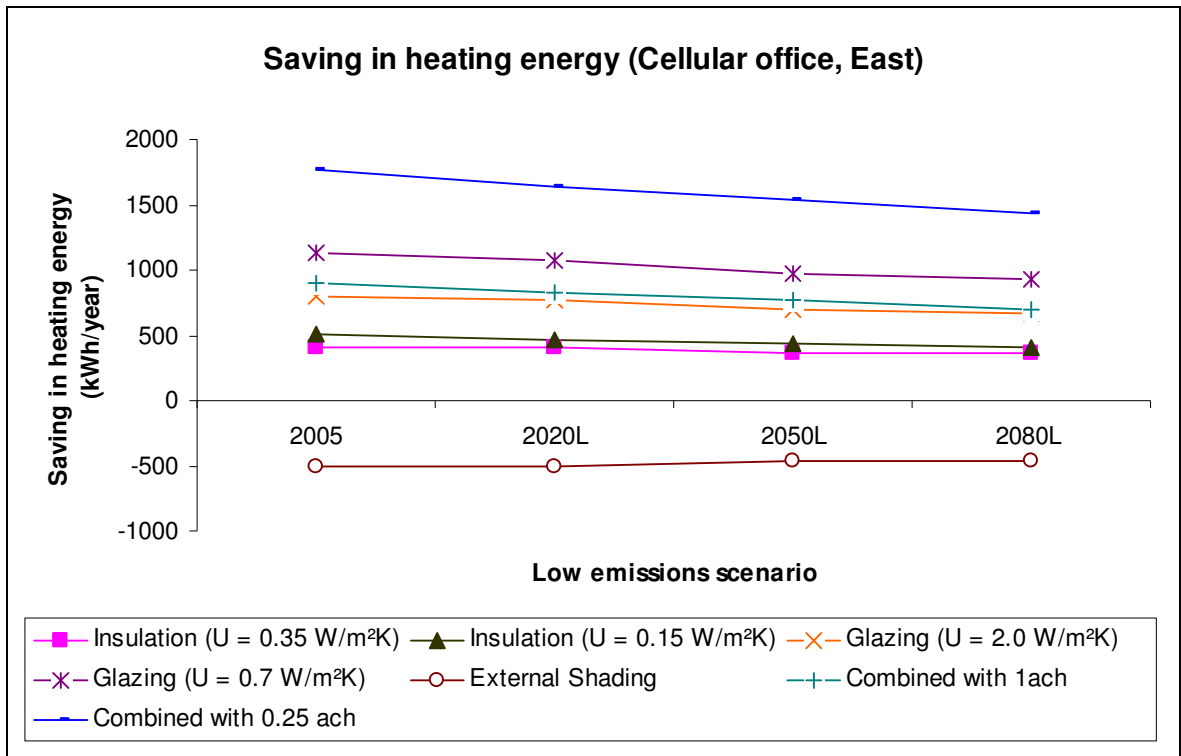
Figure 7.4 Saving in heating energy demand under different climate scenarios for the east façade of the cellular office
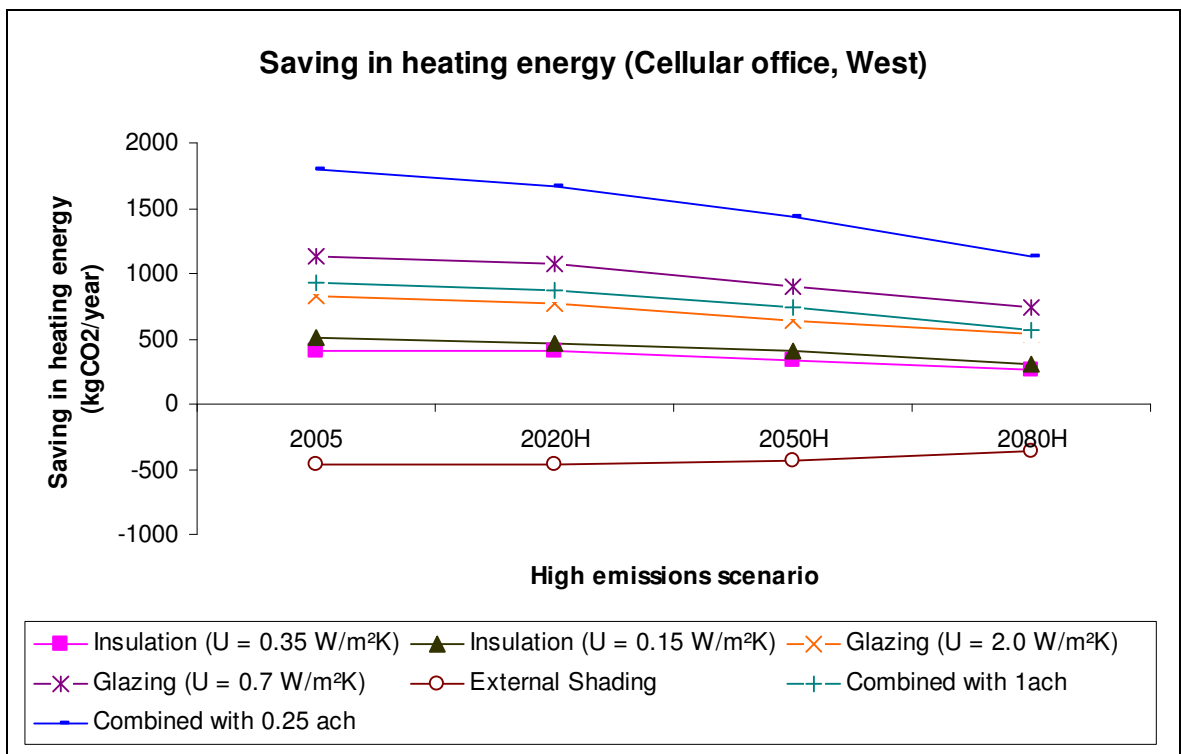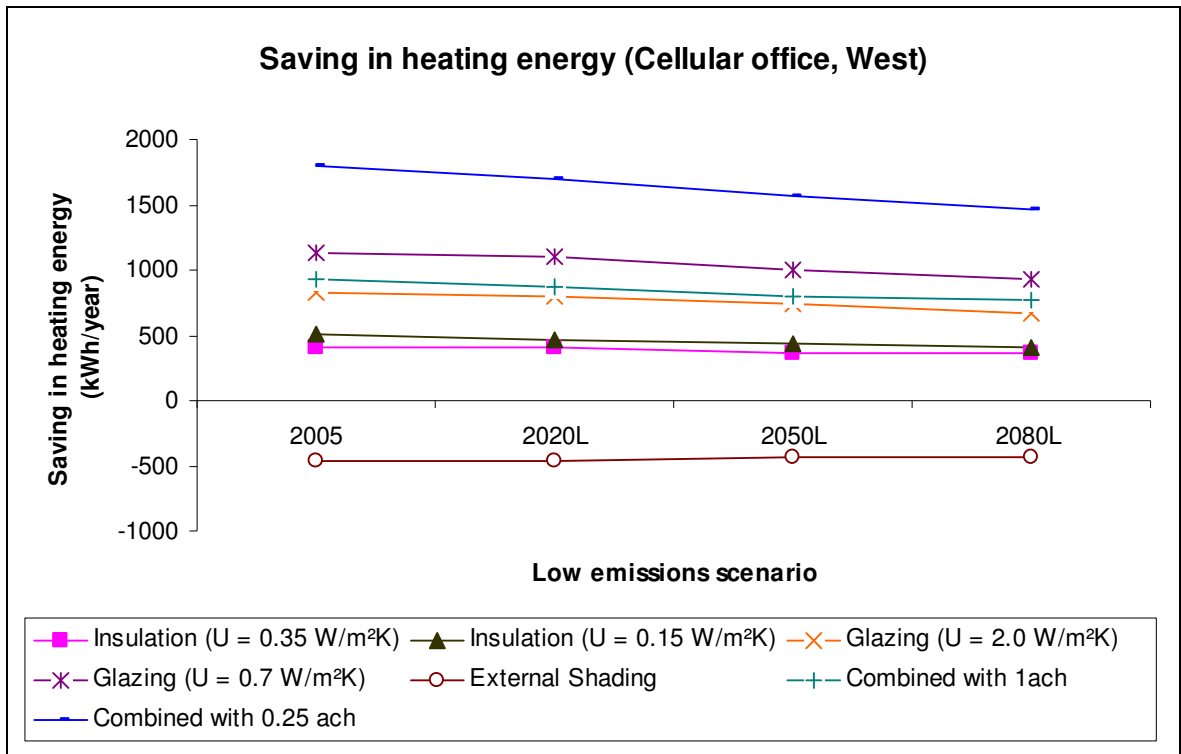
Figure 7.5 Saving in heating energy demand under different climate scenarios for the west façade of the cellular office

However, these savings decline at a faster rate relative to savings offered by other single refurbishment solutions as the climate changes. Given the relatively large glazing ratio in both offices and that single glazing is modelled in the 'as built' case, heat loss through windows is likely to be considerable under current climate conditions. While the high performance windows reduce this heat loss under current conditions, the added solar gain offsets conductive losses through the envelope; the warming of the climate means lower levels of loss are likely to be experienced, thereby reducing its effectiveness. This is particularly apparent under the high emissions climate scenarios. Conversely, while the wall insulation offers more modest savings in heating energy in comparison to the 'as built' insulation scenario, it is less sensitive to climate impacts.

For the teaching room (**Appendix F2**), due to the relatively small glazing ratio, improving the U-value of the external walls to 0.15 W/m^{2}K by increasing the insulation level used as a single solution presents the most significant savings in heating energy. High levels of insulation result in less conductive loss through the fabric. This solution becomes less effective in saving heating as the climate changes. Lower glazing ratios result in less saved heating energy. However for the teaching room this solution is relatively insensitive to climate impacts.

Using the optimum combination of all fabric measures following the 2006 Building Regulations (i.e. double glazing U-value of 2.0 W/m^{2}K, wall insulation with a U-value of 0.35 W/m^{2}K which results in improving the air-infiltration to 0.25 ach) delivers the largest savings in heating energy in all rooms.

However, this solution is very sensitive to climate change scenarios. The effectiveness of this solution to save heating energy declines at a faster rate than any other options due to a warmer future winter and for the other reasons mentioned before. Compared with air-infiltration of 1 ach, reducing the air infiltration has a considerable impact on reducing the heating energy requirement.

External shading system as a refurbishment solution performs the worst for all orientations in all rooms (**Figures 7.2-7.5** for the cellular office, **Appendix F1** for the open-plan office and **Appendix F2** for the teaching room) with more heating demand required than for any other solutions. This is due to the reduction in useful direct solar gains caused by the shading device and the blockage of a significant diffuse solar radiation (i.e. radiation that reaches a surface from all directions) particularly in the north façade. However this solution is relatively insensitive to climate change.

Although the passive refurbishment options selected can significantly reduce the occurrence of overheating, their performance results suggest it is impossible to meet thermal comfort targets using these options alone. For this reason, the use of a cooling system was investigated.

When looking at the cooling energy consumption for [cellular office (**Figure 6.20-6.23**), open-plan office (**Appendix C1**) and teaching room (**Appendix C2**)] using external shading system reduces cooling energy requirement more than any other single refurbishment option although it would result in higher heating energy demands compared to the as built. This single solution is even more effective than using a combination of refurbishment solutions.

It should be noted that while improving the U-value of the external walls and windows result in a significant saving in heating energy under different climate change scenarios, these measures result in more cooling energy under different climate change compared to the 'as built' case. This can be explained by the fact that solar energy gains can penetrate through a window and then be trapped inside while other internal heat loads (i.e. people; appliances and lighting) are much less transmitted through the well-insulated envelope than through poorly insulated one. This will lead to a significant increase in the number of hours above comfort level and therefore, more cooling energy will be required to achieve thermal comfort.

When comparing the wall insulation with the high performance glazing in terms of cooling energy, it is found that high performance glazing performs relatively better than wall insulation. This is due to the fact that the balance between the solar gains transmittance through the windows and the conduction losses through the walls is slightly in favour of the high performance glazing than high performance walls. However, it should be noted that this also depends on the glazing ratio.

For the combination of refurbishment solutions, while 'combined all with 0.25 ach' option consumes less heating energy than 'combined all with 1ach', it requires higher cooling energy and in the case of teaching room (high density, small glazing ratio) is even worse than any other single refurbishment solution in terms of cooling energy. This is due to the fact that the opportunity for the air infiltration to ventilate the space will be much less than if it is fully sealed with a very low glazing ratio.

This highlights the need for the building to be airtight and well-sealed in the winter season to reduce heating loads and leaky in summer seasons to allow cooling through natural ventilation at times of need [seal tight and ventilate right] (Roaf et al., 2008). Night cooling can play an important role in this case as long as the building security is not compromised.

7.5   Total Energy and CO_2

Results of the total energy demand for different refurbishment options are shown in (**Figures 6.24-6.27** for the cellular office, **Appendix D** for the open-plan and the teaching rooms) while results of the total CO_2 are shown in (**Figures 6.28-6.31** for the cellular office, **Appendix E** for the open plan and the teaching rooms).

In terms of total energy demand and the associated total CO_2 emissions, triple glazing (U-value = 0.7 W/m^2 K) in both the cellular and the open-plan offices is considered the best single solution while improving wall insulation to achieve a U-value of 0.15 W/m^{2}K is considered the best single option in the teaching rooms. For all rooms, combined all single solutions to achieve air infiltration of 0.25 ach present the best combined solutions compared to 1 ach. External shading is considered the worst option which results in a significant increase in both total energy and CO_2 emissions compared to the as-built case for all climate change scenarios.

The total energy and the associated CO_2 emissions results suggest that substantial energy and CO_2 savings are possible, particularly in the dominant heating season (October-May). Climate change has a large effect on mainly heating demands since the heating season is longer than the cooling season (June-September) even under different climate change scenarios.

In the UK, increases in cooling energy demands due to global warming might be outweighed by reductions in the need for heating energy. While sensitivity to different climate change scenarios varies across the alternative refurbishment solutions, changing their relative performance significantly in some cases, the ranking of the options remains constant across both low and high emission scenarios. Consequently, in terms of thermal efficiency, climate change uncertainties are unlikely to affect which options deliver the greatest overall benefit.

However, within AUDE decision makers, the choice to invest in a particular refurbishment option will be governed by its thermal efficiency, its associated CO_2 emissions and cost effectiveness.

7.5.1 *CO_2 Emissions Considerations*

Depending on the type of fuel used, the net effect on CO_2 emissions might be an increase even where the overall demand for the delivered energy is reduced. Under climate change, the demand for heating energy decreases continuously and the CO_2 emissions are accordingly lower as well. Cooling demand is increased compared to the current climate. The net effect on energy use and CO_2 emissions depends on the balance between the effect on heating and cooling needs.

From heating and cooling energy loads figures for different rooms (**Figures 6.16-6.31**) for cellular office, **Appendices B-E** for open-plan and teaching rooms), heating accounts for vastly greater energy use and associated CO_2 emissions than does cooling. Consequently, the impact of large percentage increases in cooling demand can be offset by smaller percentage reductions in heating demand. However, the most important factor in this balance is the relative CO_2 intensity of the electricity and gas supplied to buildings.

Thus, based on current energy mix values, savings in CO_2 emissions regarding heating loads are more than the additional increases in the emissions due to the increases in the cooling loads despite the fact that the current energy mix shows that specific CO_2 emissions for electricity is slightly more than two times the gas emissions [0.422 $kgCO_2$/kWh and 0.194 $kgCO_2$/kWh respectively] (CIBSE, 2006). **Figures 7.6-7.9** present the net CO_2 savings in the cellular office while the results for the open-plan and the teaching room are presented in **Appendix G**. The net CO_2 savings were calculated by subtracting the associated CO_2 savings in heating energy [**Figures 7.2-7.5** for cellular office, **Appendix F** for the open-plan and the teaching rooms] using refurbishment options from the increases in the associated CO_2 from the cooling energy using energy mix values.

7.5.2   *Cost Considerations*

Cost effectiveness is assumed to include refurbishment costs (i.e. costs for materials and installation) and operational costs (i.e. costs for meeting heating and cooling energy demands). These are particular to each climate change scenario and could influence which options prove to be cost effective in the longer term. **Figures 7.10-7.13** present the net savings in operational cost for cellular office and for different refurbishment options under low and high emissions scenario. Results for open-plan and teaching room are shown in **Appendix H**.

These figures were derived from the difference between savings in heating energy and the additional costs incurred by the cooling energy of using each of the refurbishment solutions. Estimates of the economic cost of energy for the HE buildings, gas for the heating system and electricity for the cooling system, are based on current market prices and are assumed to be 3p per kWh and 10p per kWh respectively (British Gas, 2009).
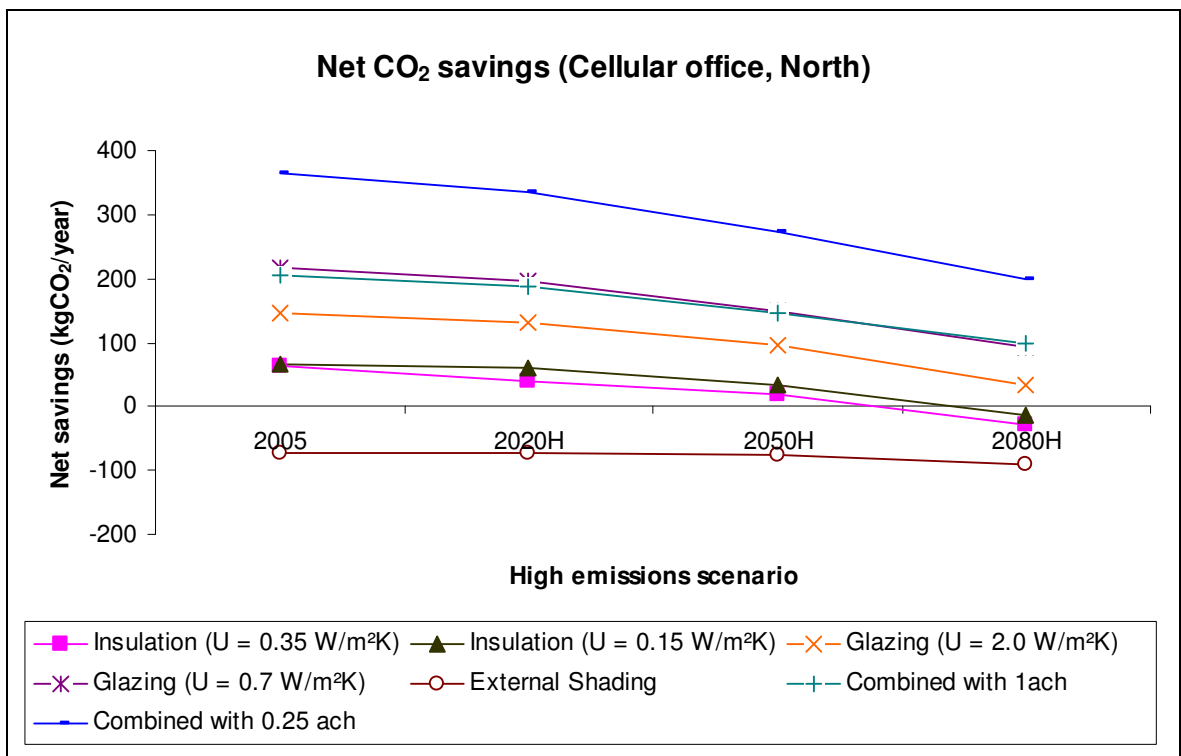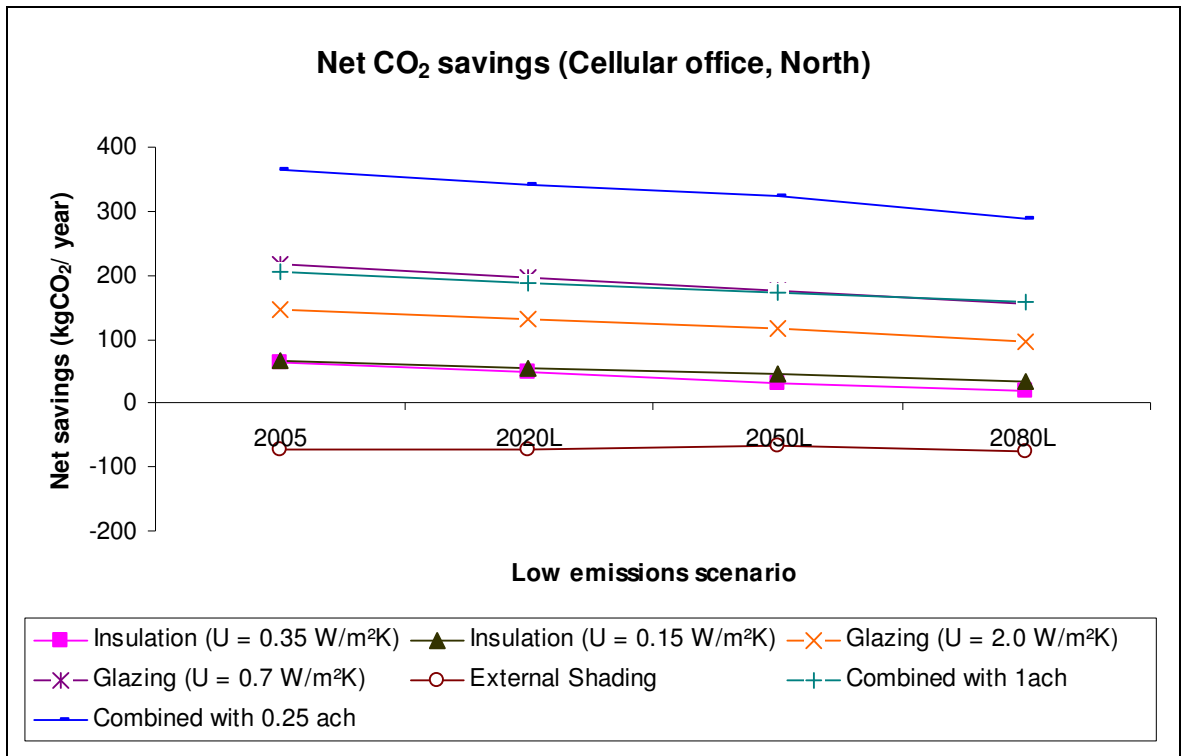
Figure 7.6 Net saving in CO_2 emissions under different climate scenarios for the north façade of the cellular office
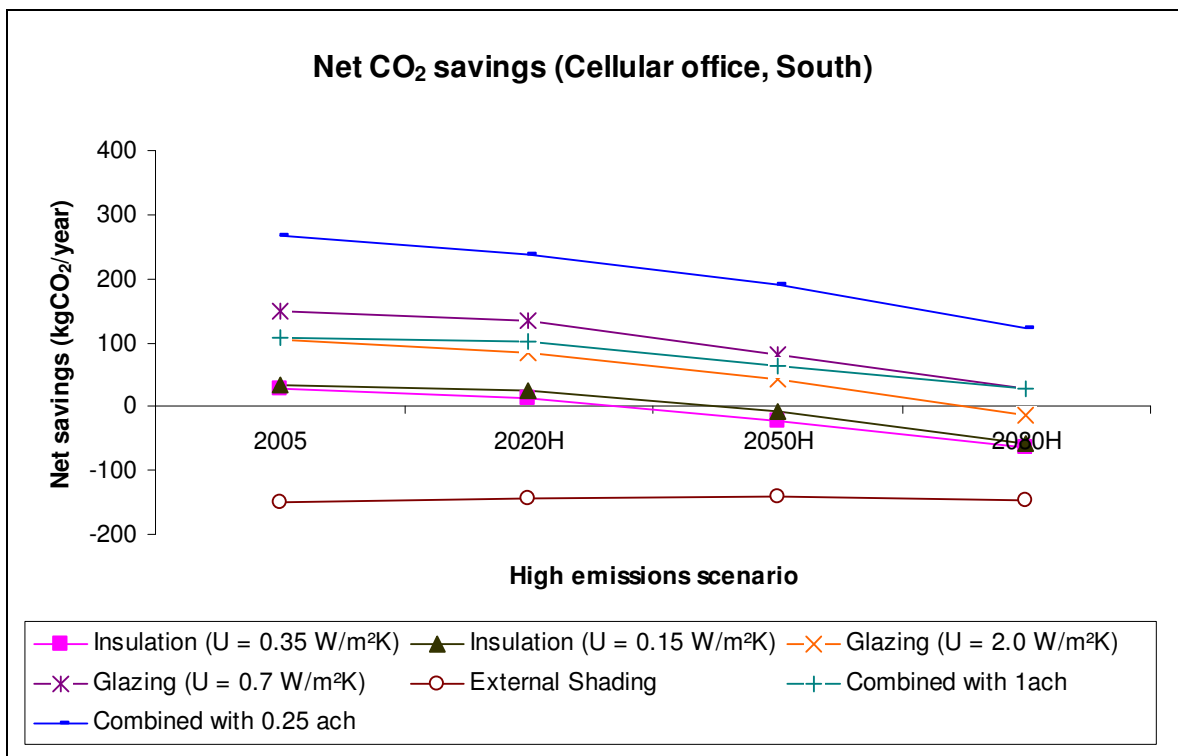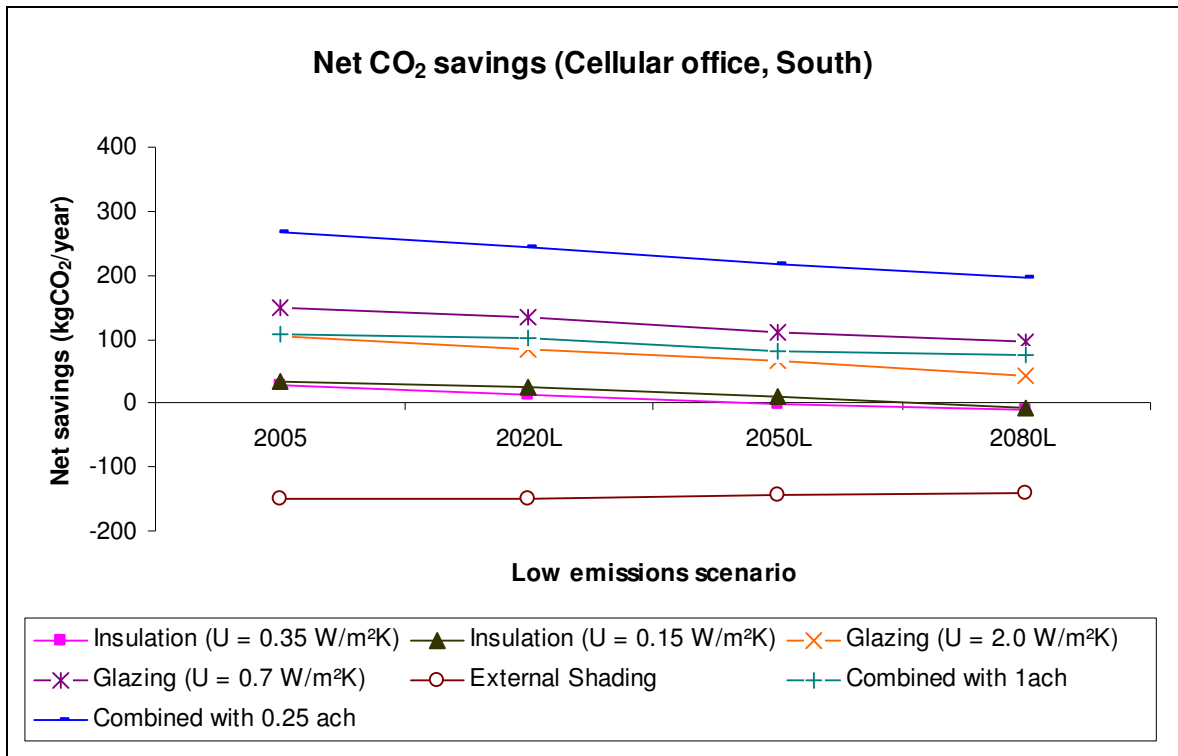
Figure 7.7 Net saving in CO_2 emissions under different climate scenarios for the south façade of the cellular office
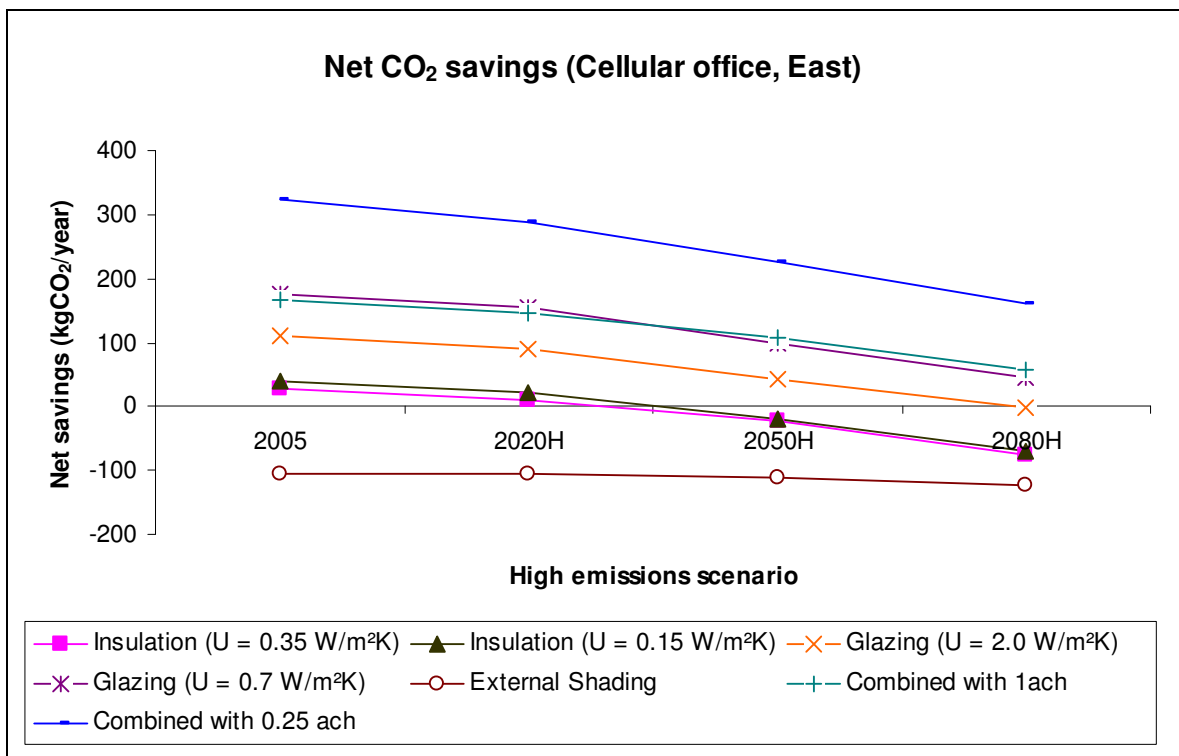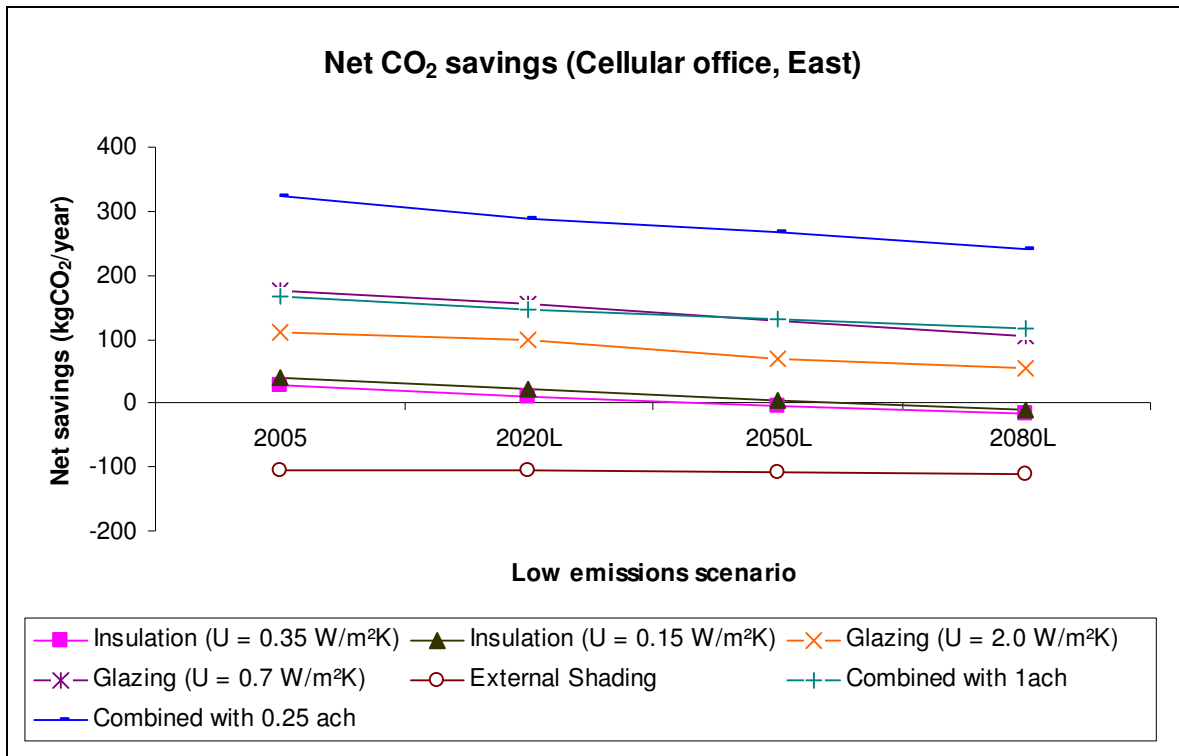
Figure 7.8 Net saving in CO_2 emissions under different climate scenarios for the east façade of the cellular office
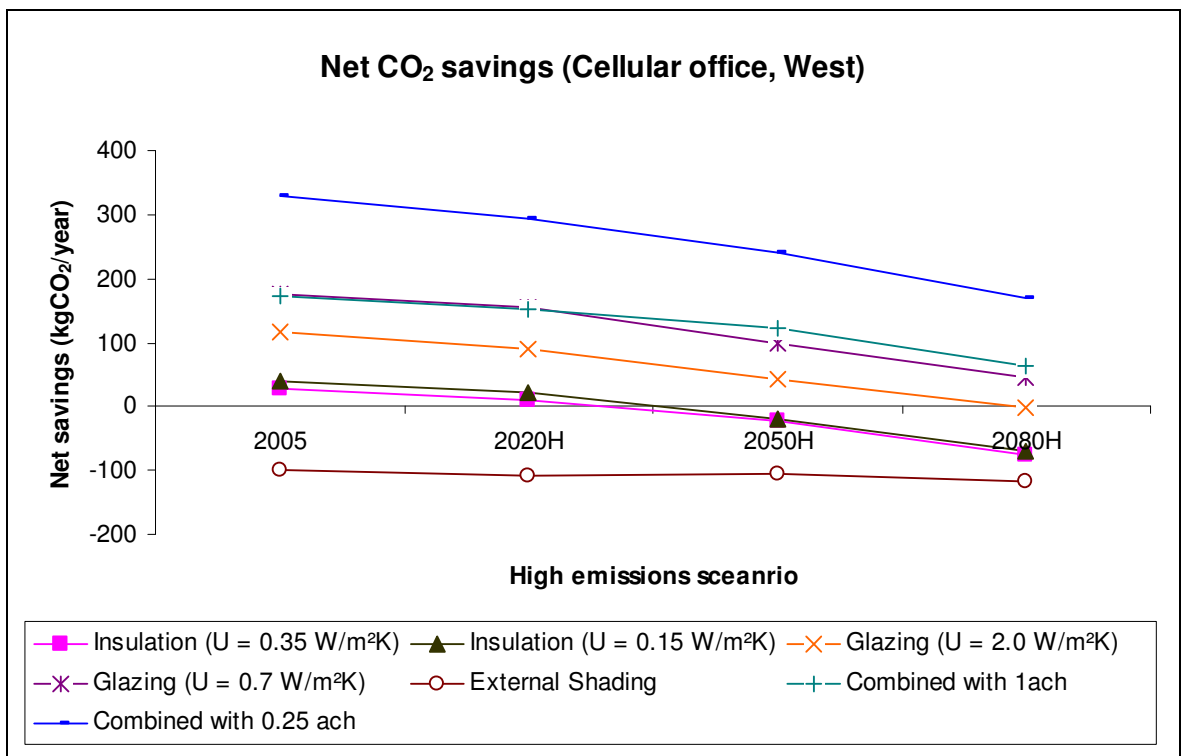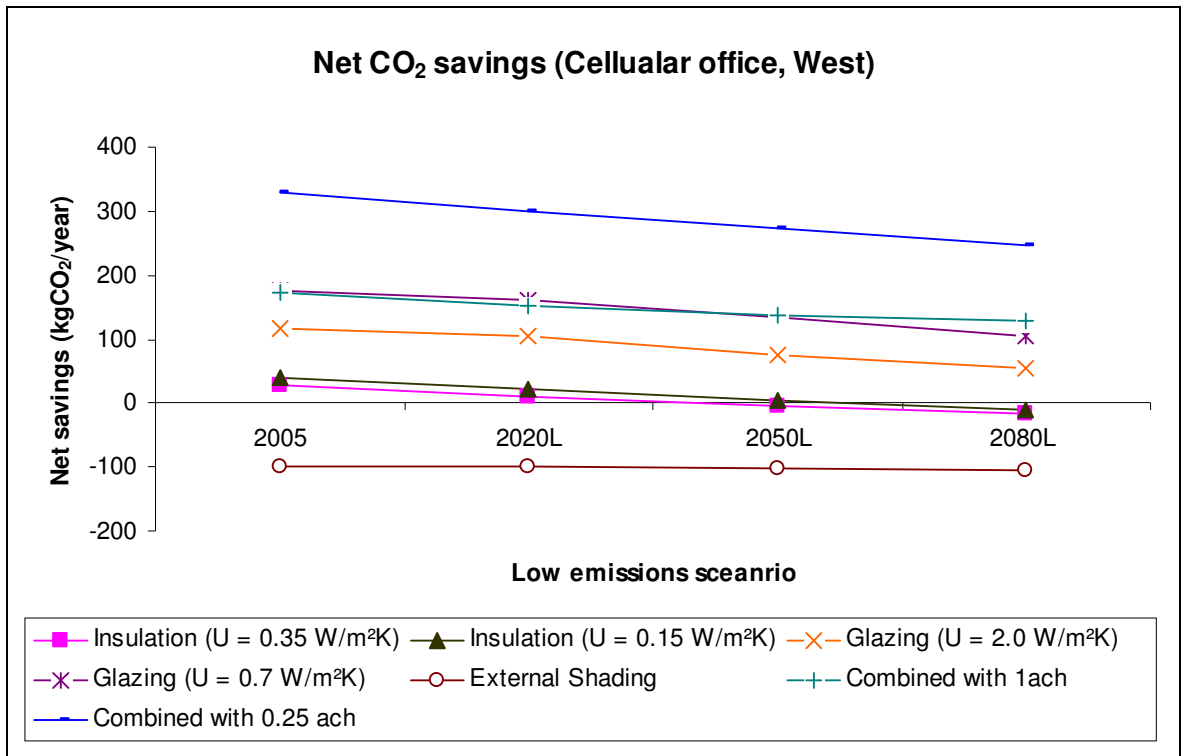
Figure 7.9 Net saving in CO_2 emissions under different climate scenarios for the west façade of the cellular office
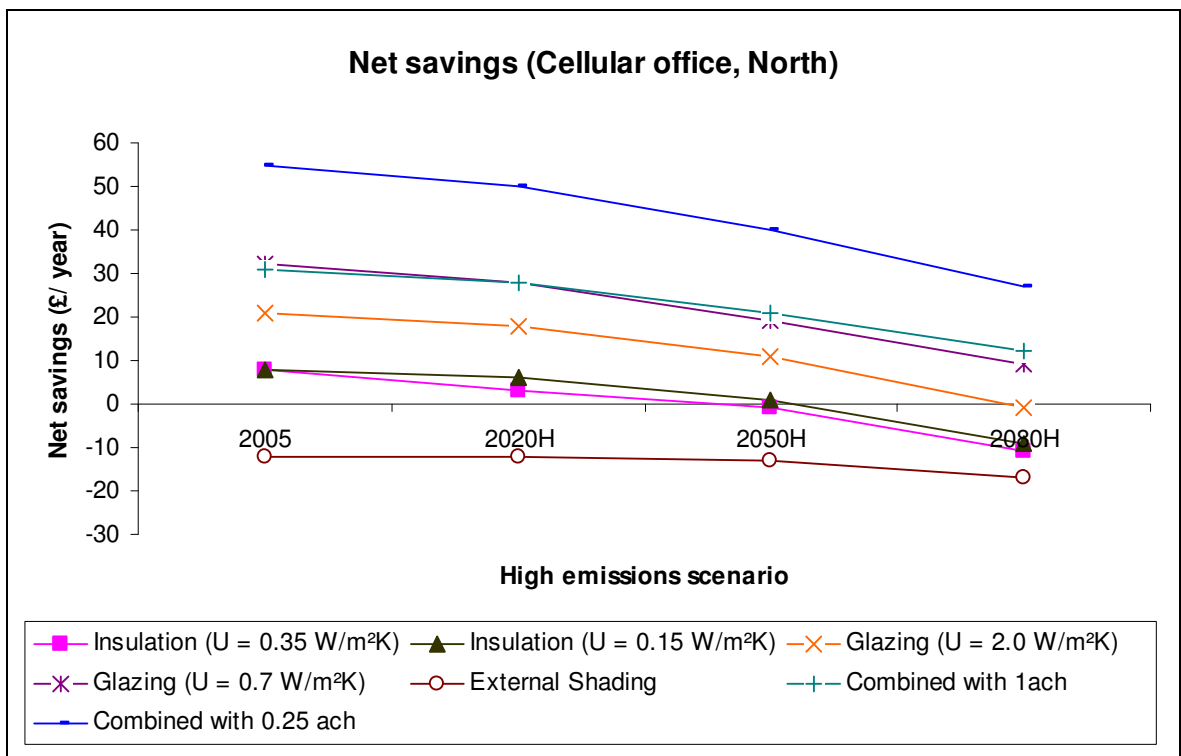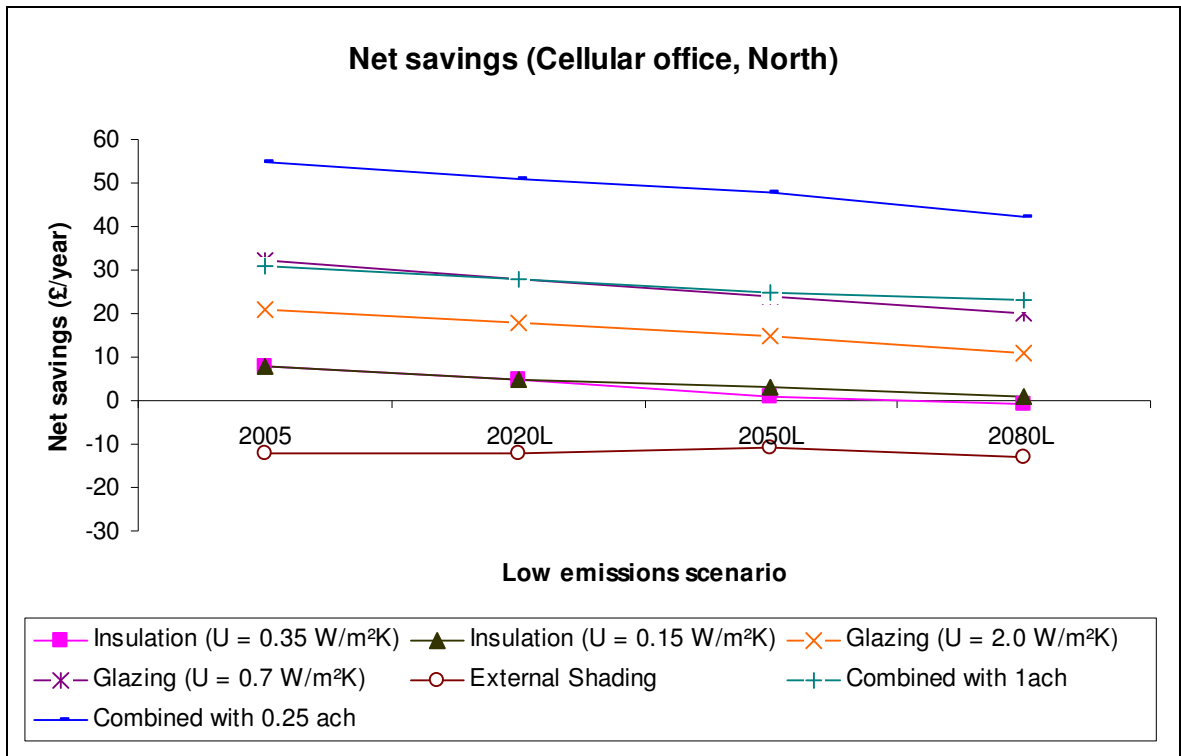
Figure 7.10 Net saving in operational cost under different climate scenarios for the north façade of the cellular office

Net savings(Cellular office, South)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net savings (Cellular office, South)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach
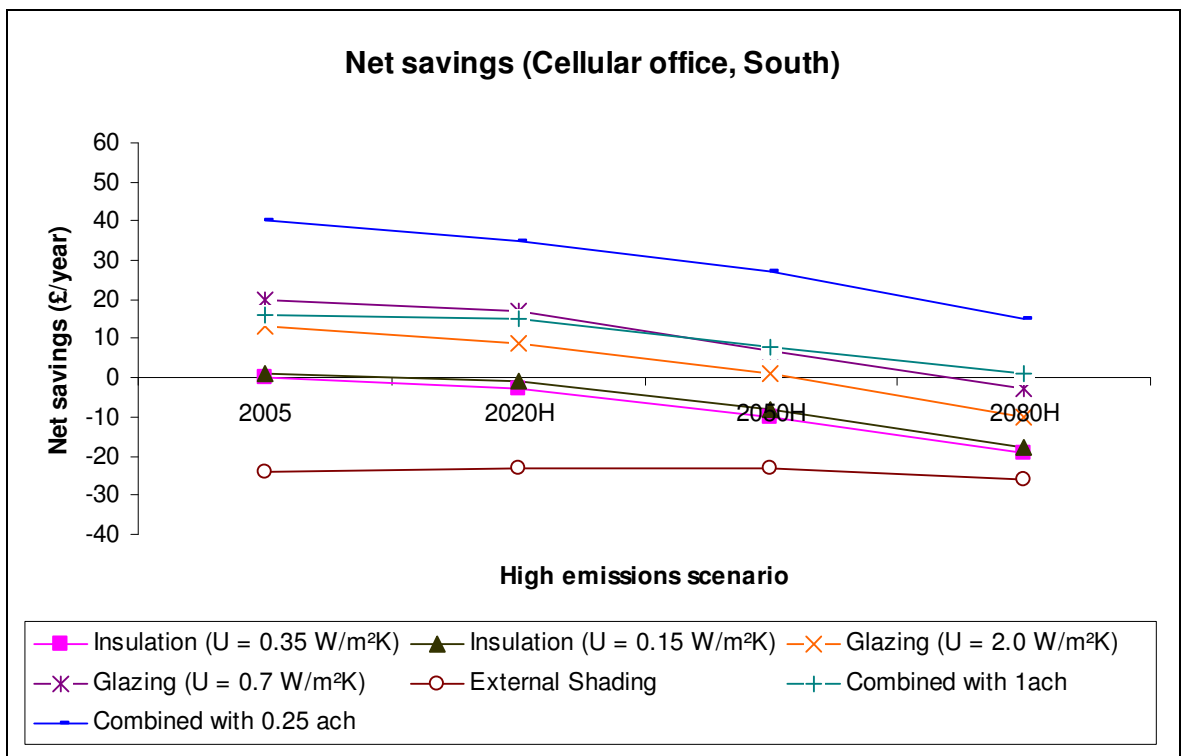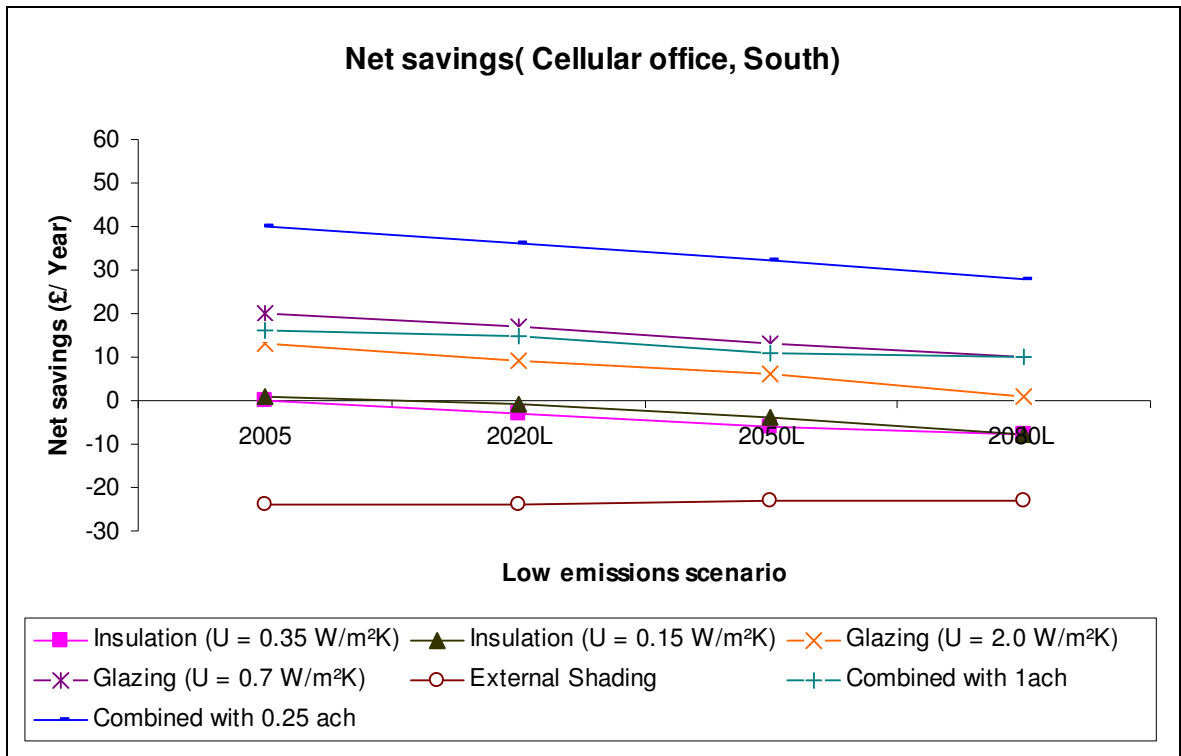
Figure 7.11 Net saving in operational cost under different climate scenarios for the south façade of the cellular office
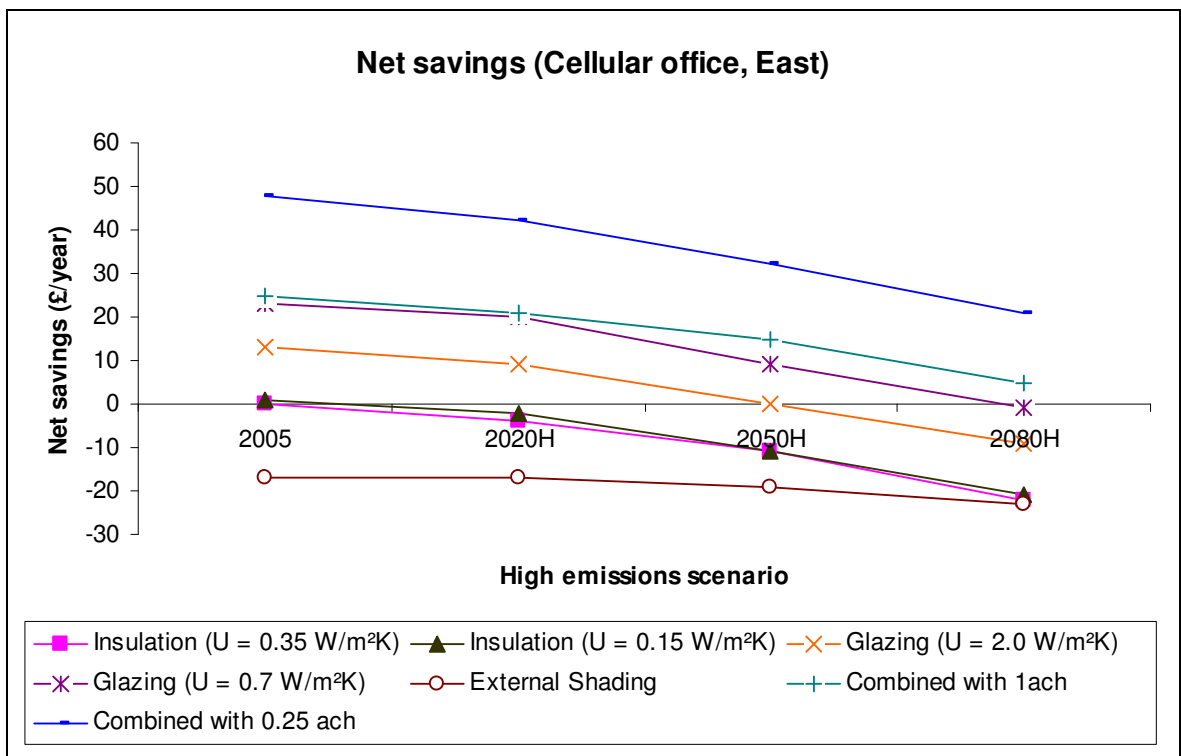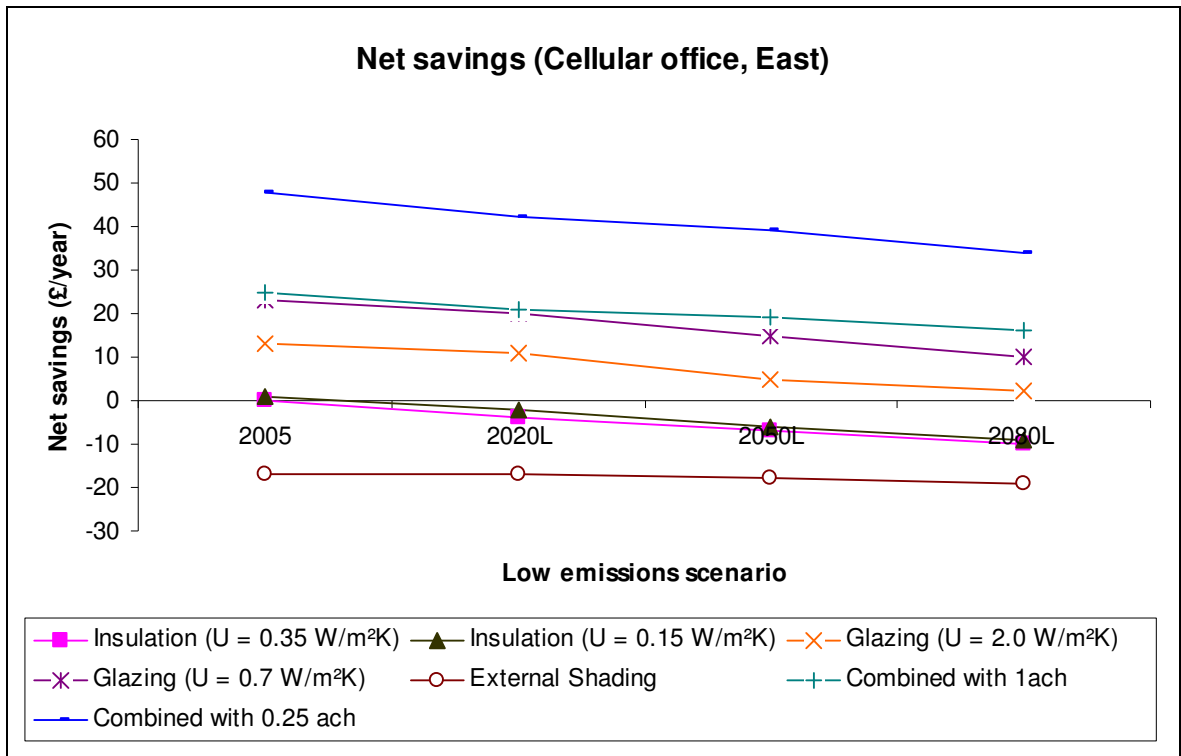
Figure 7.12 Net saving in operational cost under different climate scenarios for the east façade of the cellular office
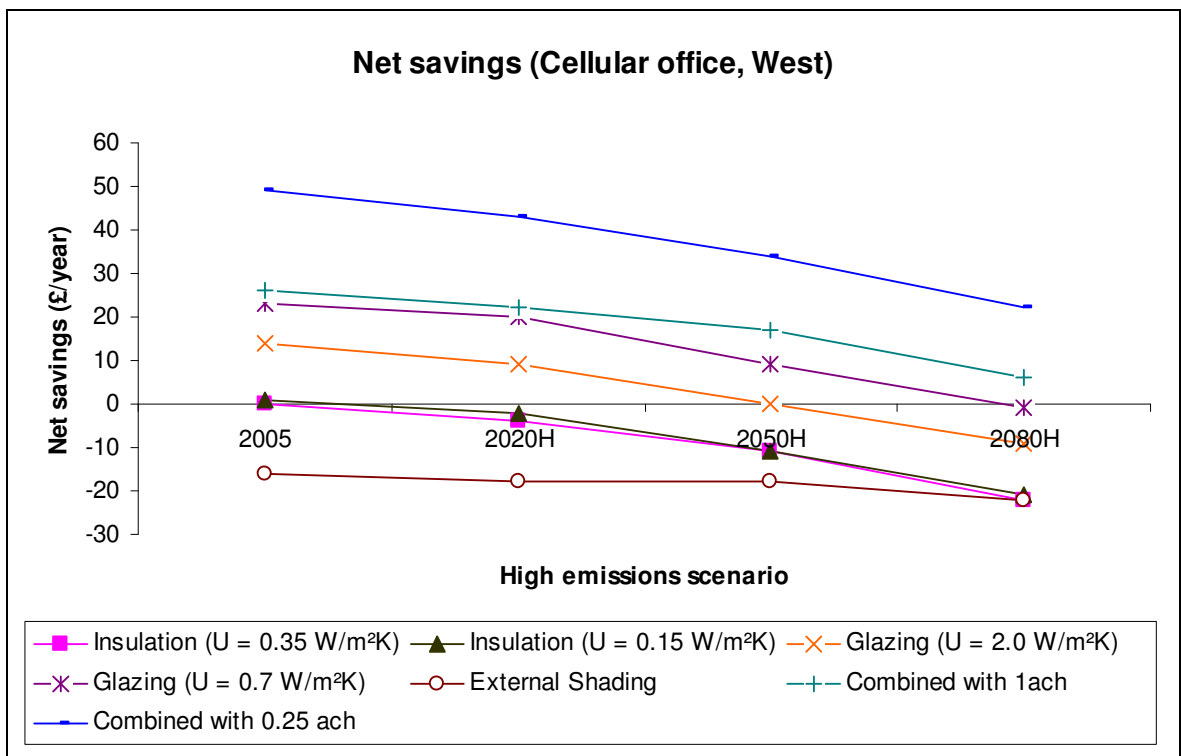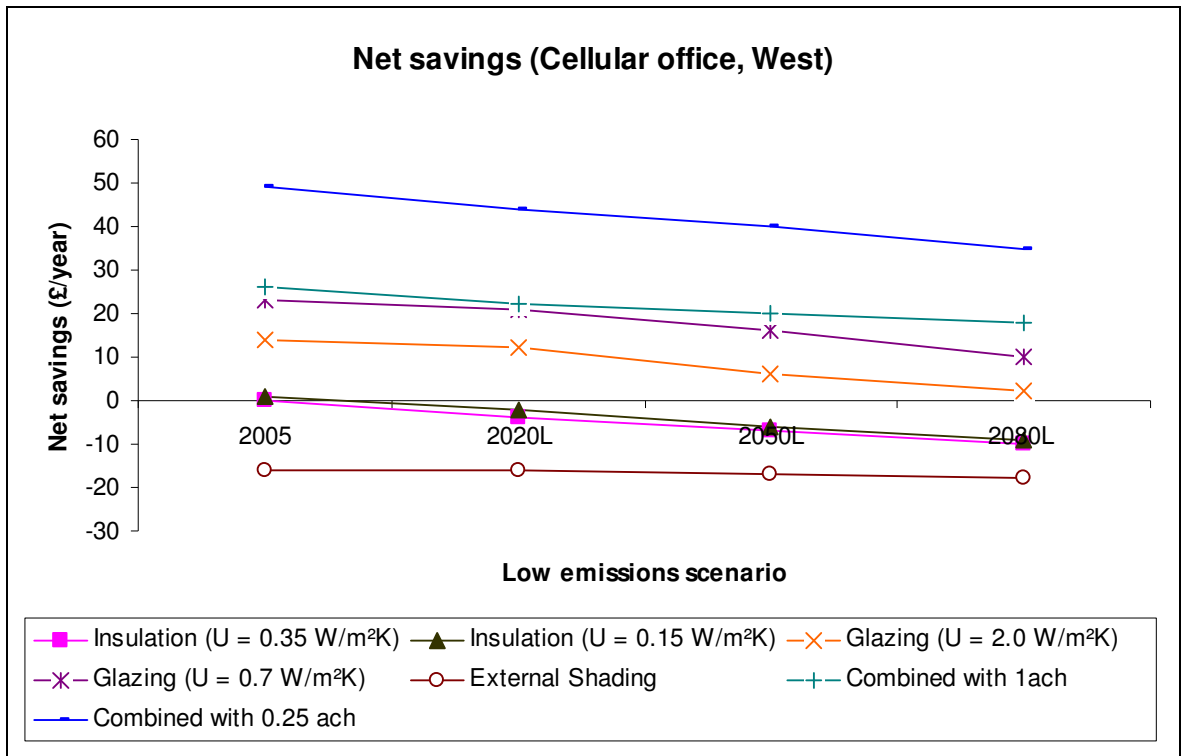
Figure 7.13 Net saving in operational cost under different climate scenarios for the west façade of the cellular office

It is expected that these values are likely to increase due to the uncertainty in future energy prices (IEA, 2009). However, these costs are assumed to remain constant under different climate change scenarios and for different time slices to allow comparison.

Referring to **Figures 7.6-7.13** for the cellular office, **Appendices G-H** for the open-plan and the teaching rooms, CO_2 and monetary savings decline significantly under low and high emission scenarios and it is clearer in the high emissions scenario. However, results for external shading suggest that this option is insensitive to climate change impacts compared to other options. The changing relationship between the associated CO_2 emissions and financial savings for the heating energy and the increases in cooling energy emissions and costs remains relatively constant for the external shading under different climate change scenarios.

While some refurbishment options (e.g. high performance glazing and all solutions combined) provide net financial and CO_2 emissions savings and others incur extra cost and CO_2 emissions (e.g. wall insulation and external shading) the ranking of these refurbishment options remain the same. The changing relationship between financial savings in heating energy and increases in cooling energy costs, due to different estimated costs of each energy type, has not changed the ranking of refurbishment options when compared to that based on total savings in CO_2 emissions.

However, these calculations account for the net savings in operational CO_2 and the cost of each option but do not include either the embodied CO_2 of each option or the capital cost both of which are likely to result in some differences in the rank as will be discussed in **(Section 7.5.3)**.

7.5.3   Embodied CO_2 and Capital Cost Considerations

Embodied CO_2 accounts for emissions during procuring raw materials, converting them to construction materials, products or components, transporting and building them into structures but does not include maintenance, reuse or final disposal (Thomas and Fordham, 2006). **Table 7.1** shows the embodied CO_2 per m^2 of each refurbishment option, and the total embodied CO_2 per room while **Table 7.2** shows the capital cost per m^2 of supplying and installing each option, their projected service life, and the total cost per room.

Table 7.1 Embodied CO_2 for different suggested refurbishment options

Refurbishment option	Embodied CO_2 $(kgCO_2/m^2)$ *	Embodied CO_2 per room $(KgCO_2)$		
		Cellular office	**Open-plan office**	**Teaching room**
Insulation (U = 0.35 W/m^{2}K)	2.90	18	71	141
Insulation (U = 0.15 W/m^{2}K)	4.50	28	109	219
Glazing (U = 2.0 W/m^{2}K)	120	591	3564	648
Glazing (U = 0.7 W/m^{2}K)	280	1380	8316	1512
External Shading	36	177	1069	194
Combined all options (1 ach/ 0.25 ach) **	158.9	786	4704	983

* Derived from (Hammond and Jones, 2010) and (Anderson et al., 2009)

** [Insulation (U= 0.35 W/m^{2}K), Glazing (U = 2.0 W/m^{2}K) and External Shading]

Whilst glazing replacement as a single refurbishment solution appears to provide the largest savings in operating cost and CO_2 emissions, it has the highest capital cost and the highest

Table 7.2 Summary of cost data for different suggested refurbishment options

Refurbishment option	Capital cost ($£/m^2$)[1]	Service life (Years)[2]	Cost per room (£)		
			Cellular office	Open-plan office	Teaching room
Insulation (U = 0.35 W/m^{2}K)	50	40	314	1215	2430
Insulation (U = 0.15 W/m^{2}K)	60	40	376	1458	2916
Glazing (U = 2.0 W/m^{2}K)	450	25	2218	13365	2430
Glazing (U = 0.7 W/m^{2}K)	600	25	2957	17820	3240
External Shading	250	30	1232	7425	1350
Combined all options (1 ach / 0.25 ach)	750	N/A[3]	3764	22005	6210

[1] Source (Langdon, 2009)

[2] Source (GreenSpec, 2010; Kingspan, 2010)

[3] Service life for 'combined all options' is calculated separately for each refurbishment option

embodied CO_2 (**Table 7.1 and Table 7.2**) compared to other single refurbishment options (wall insulation and external shading). Results from (**Tables 7.1 and Table 7.2**) highlight how the inclusion of the embodied CO_2 and the capital cost might change the rank of refurbishment solutions. While, in terms of thermal performance, glazing replacement is the most effective single refurbishment option in the cellular and the open-plan offices, the relative short service life coupled with high capital costs and embodied CO_2 mean that it is likely to be the least cost effective and environmentally friendly solution. Conversely, longer service lives, lower capital costs and embodied CO_2 associated with improved wall

insulation mean their economic performance is better than their relative thermal performance
and it would be a more environmentally friendly solution than glazing replacement.

The large variations in the capital cost and the embodied CO_2 of refurbishment solutions
suggest that the most thermally efficient refurbishment solutions might not necessarily be the
most economically efficient or environmentally friendly. To evaluate the relative
environmental impact and the cost effectiveness of each refurbishment options over the
whole life (which is assumed in this study to be the end of 2079 and therefore, some of them
are replaced more than one time during this period), two ratios have been suggested.

- For the relative environmental impact evaluation, the net Operational CO_2 savings to
  the Embodied CO_2 Ratio (OER) is calculated for each option with higher values
  reflect less environmental impact [i.e. more environmentally friendly option].

- For the cost effectiveness evaluation, the net operational cost savings to the capital
  cost or in other words Benefit Cost Ratio (BCR) is used with higher values indicate
  greater cost effectiveness [i.e. more economically efficient] (Ardalan, 2000).

1. Relative Environmental Impact

OER is used to assess the relative environmental impact. OER is calculated for each
refurbishment option over 75 years (2005-2079) as follows:

$$OER = \frac{\sum_{0}^{T} \text{Net operational } CO_2 \text{ savings of a given refurbishment option}}{\text{Embodied } CO_2} \qquad \textbf{Eqn 7.1}$$

where T is the service lifetime of a given refurbishment option. 2005 is taken to be the current year (year 0) and 2079 is taken to be the year 75.

Clearly due to the different service life of refurbishment options (**Table 7.2**), some of them will be replaced 2 times over the 75 years (e.g. wall insulation) or 3 times (e.g. glazing and external shading).

OER is calculated for different refurbishment options in three stages. The first stage assumes that no climate change is occurred over the service life of any refurbishment options. Consequently, the net CO_2 savings by each refurbishment option remain constant over its service life. The second stage of the calculation considers the impact of climate changes projected under the low emissions scenario. The third stage considers the impact of climate changes projected under the high emissions scenario. Similar to previous analysis (e.g. heating, cooling energy and associated CO_2 emissions), rather than being concerned with absolute values, the main purpose is to consider changes in relative OER.

Results from these stages of calculations are summarised in (**Figures 7.14-7.17)** for the cellular office while results for the open-plan office and the teaching room are summarised in (**Appendix I**).

Results from the first stage of calculations (No climate change scenario) in the cellular office (**Figures 7.14a-7.17a**) suggest that the wall insulation (U-value = 0.35 W/m^{2}K) appears to have the highest OER (i.e. the lowest environmental impact) compared to the other single and combined refurbishment solutions. This is due to the lower embodied CO_2 compared to the other refurbishment options. OER is more in favour of wall insulation than other refurbishment solutions.
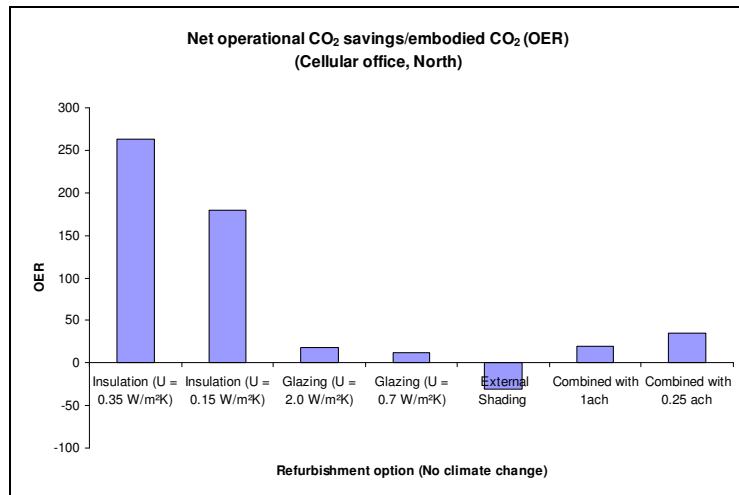
(a) No climate change
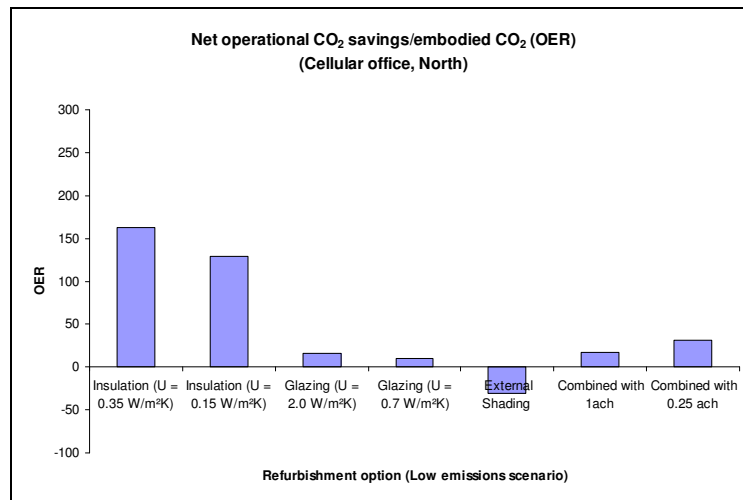
(b) Climate change-Low emissions scenario
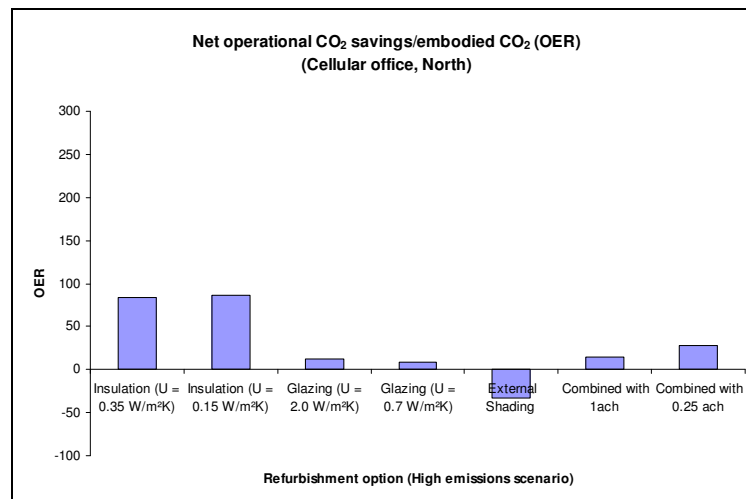
(c) Climate change-High emissions scenario

Figure 7.14 OER for the north façade of the cellular office
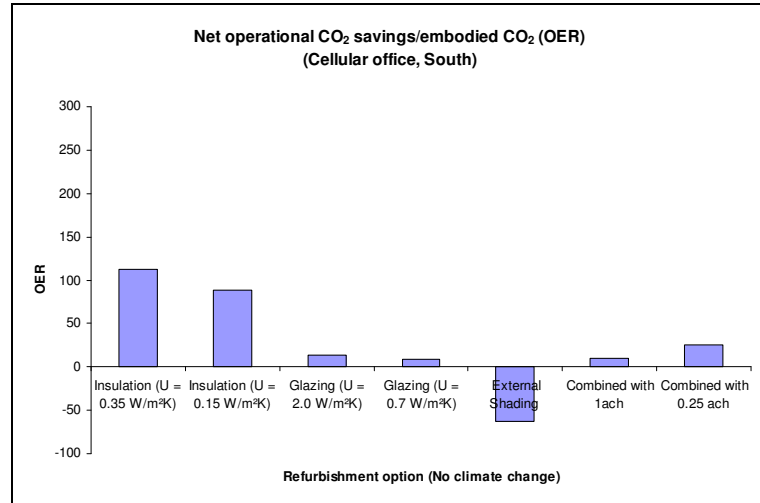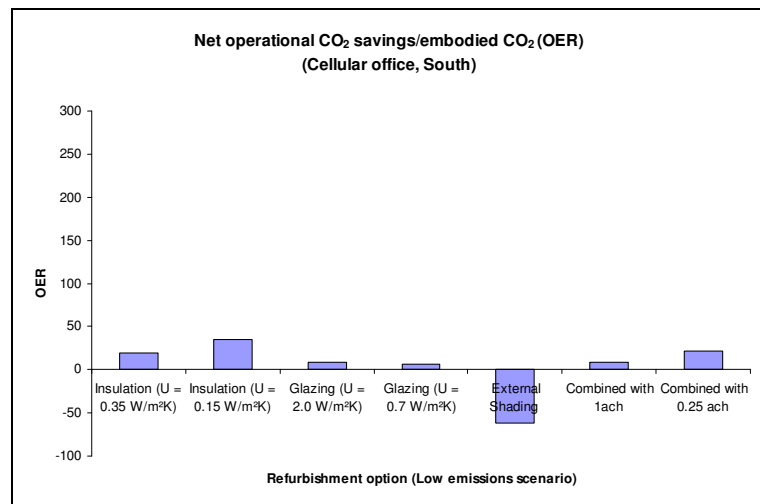
(a) No climate change

(b) Climate change-Low emissions scenario
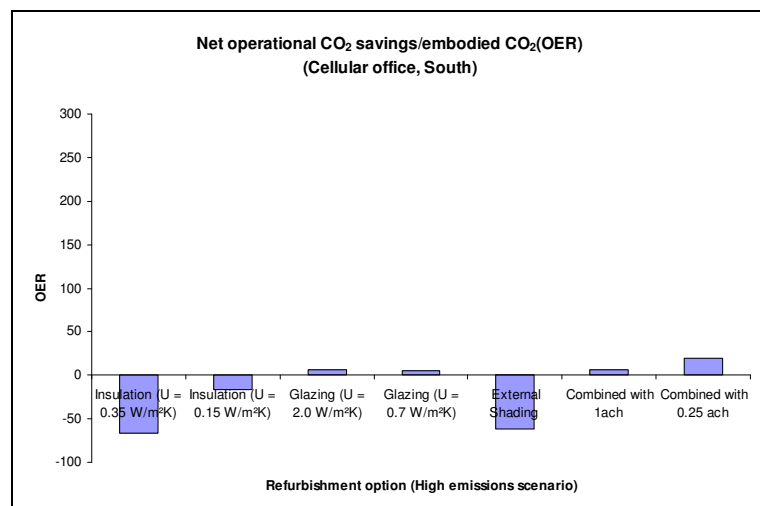
(c) Climate change-High emissions scenario

Figure 7.15 OER for the south façade of the cellular office
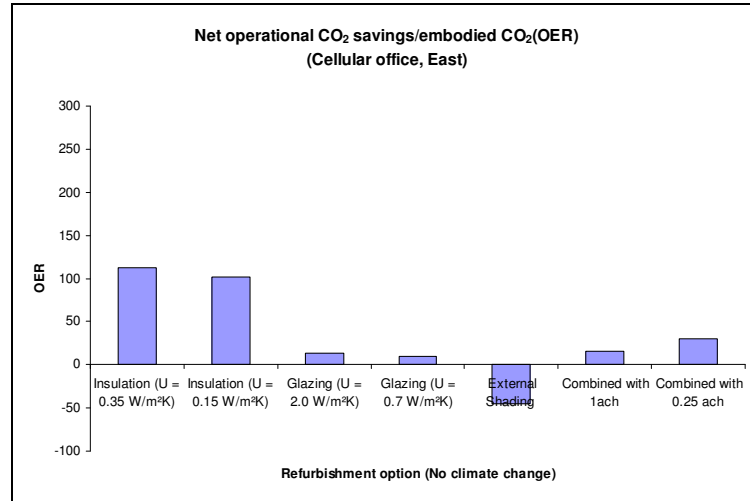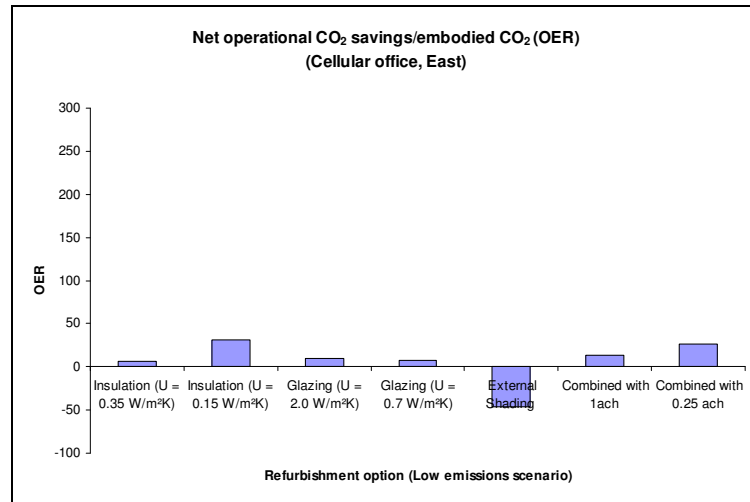
(a) No climate change

(b) Climate change-Low emissions scenario
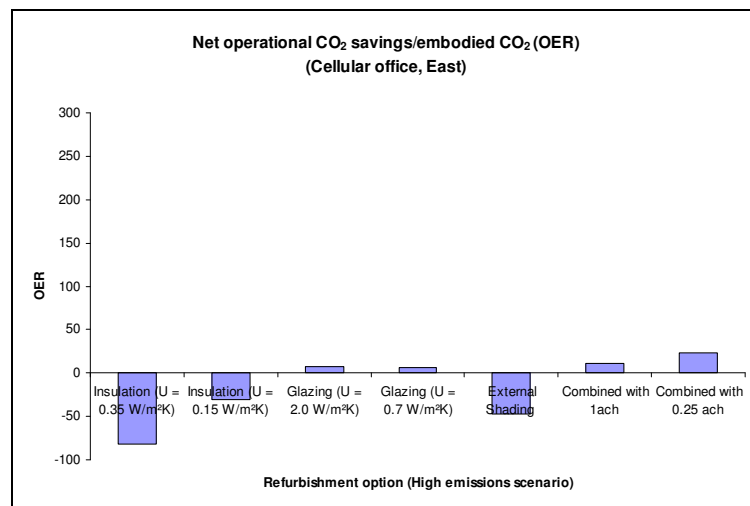
(c) Climate change-High emissions scenario

Figure 7.16 OER for the east façade of the cellular office
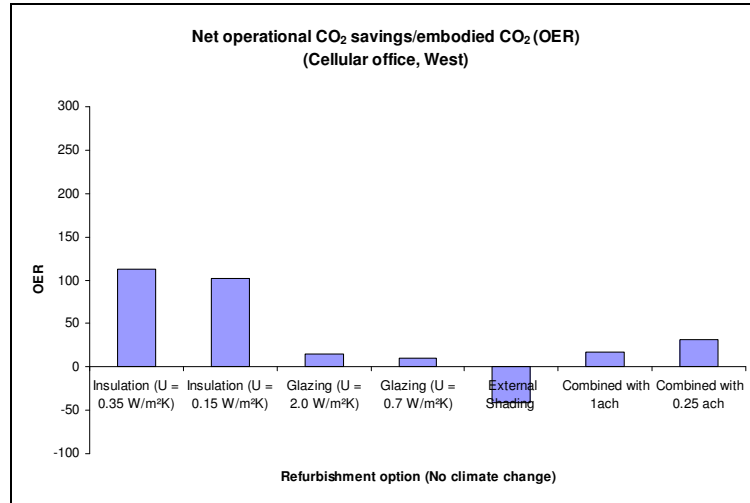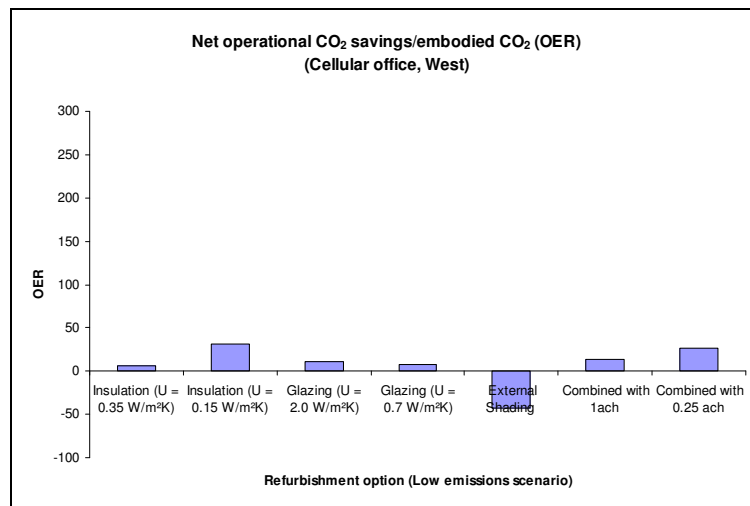
(a) No climate change

(b) Climate change-Low emissions scenario
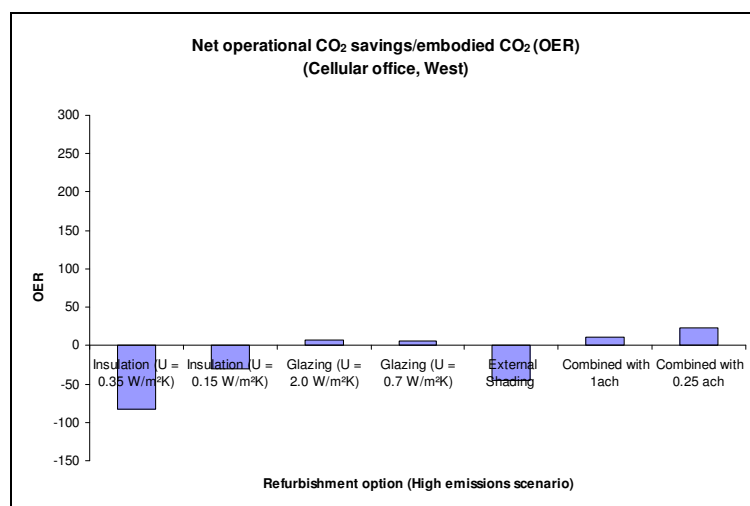
(c) Climate change-High emissions scenario

Figure 7.17 OER for the west façade of the cellular office

External shading has the lowest OER and consequently, the highest environmental impact (**Figures 7.14a-7.17a**). 'Combined all with 0.25 ach' has lower OER (i.e. lower environmental impact) than 'combined all with 1 ach' option (**Figures 7.14a-7.17a**). However, results from the second and third stages of calculations suggest that the effectiveness of the wall insulation (U-value = 0.35 W/m^2K and 0.15 W/m^2K) reduces at a faster rate under low and high emissions scenarios compared to the other refurbishment solutions (**Figures 7.14b-7.17b**) and (**Figures 7.14c-7.17c**).

The introduction of climate change impacts changes the wall insulation option (U-value = 0.35 W/m^2K) from being the lowest environmental impact solution to become the highest environmental impact solution. This can be seen clearly under the high emissions scenario for the south, east and west façade (**Figures 7.15c-7.17c**).

Despite having the lowest embodied CO_2 (**Table 7.1**), the changing relationship between reductions in the heating energy and increases in the cooling energy (and their associated CO_2 emissions) of the wall insulation (U-value = 0.35 W/m^2K and 0.15 W/m^2K) has a considerable impact on the net CO_2 savings and therefore on the OER. This would change the ranking of the refurbishment options based on OER with climate change impacts when compared to that based on OER without climate change impacts.

Reductions in OERs highlight the sensitivity of the environmental impact of different refurbishment options to climate variables. The environmental impact of the wall insulation (U-value = 0.35 W/m^2K and 0.15 W/m^2K) is the most sensitive of the refurbishment options to changes in climate scenario. Such sensitivity results from the valuation of the relatively high cooling loads introduced and their associated high CO_2 intensity which, when compared to the embodied CO_2 begins to reduce the net CO_2 savings [the numerator of the OER

equation]. The high performance glazing (U-value = 2.0 W/m^{2}K and 0.7 W/m^{2}K) and 'the combined all options' (1 ach and 0.25 ach) are relatively less sensitive to changes in climate scenario than the wall insulation (U-value = 0.35 W/m^{2}K and 0.15 W/m^{2}K). Despite the higher embodied CO_2 [denominator in the OER equation] for those options compared to the wall insulation, the changing relationship between reductions in CO_2 from the heating energy and increases from the cooling energy using these refurbishment options and therefore, their net savings [the numerator in the OER equation] will not significantly change the OER ratio.

Results for the open-plan office and the teaching room are shown in **Appendix I1** and **Appendix I2** respectively. For the open-plan office (**Appendix I1**), results for both excluding and including climate change impacts suggest that glazing (2.0 W/m^{2}K) has the highest OER (i.e. lowest environmental impact) compared to other single refurbishment solutions under both 'no climate change' and under 'low emissions' scenarios. Under high emissions scenario, glazing (0.7 W/m^{2}K) has the highest OER compared to other single refurbishment options. Wall insulation (0.35 W/m^{2}K) has the lowest OER for all climate scenarios. 'Combined all with 0.25 ach' has higher OER (i.e. lower environmental impact) compared to 'combined all with 1 ach' for different climate scenarios. For the teaching room (**Appendix I2**), results for both excluding and including climate change impacts suggest that glazing (0.7 W/m^{2}K) has the highest OER (i.e. lowest environmental impact) compared to other single refurbishment solutions. External shading has the lowest OER. 'Combined all with 0.25 ach' has higher OER (i.e. lower environmental impact) compared to 'combined all with 1 ach' for different climate scenarios.

2. Cost Effectiveness

Benefit Cost Ratio (BCR) is used to evaluate the relative cost effectiveness of each refurbishment option (Ardalan, 2000). BCR is calculated for each refurbishment option over 75 years (2005-2079) as follows:

$$\text{BCR} = \frac{\displaystyle\sum_{0}^{T} (\text{Net cost savings of a given refurbishment option}) \, / \, (1 + r)^t}{\text{Capital cost}} \qquad \textbf{Eqn. 7.2}$$

where T is the service lifetime of a given refurbishment option, r the discount rate (3.5 %) and t the year.

Discounted cash flows (DCFs) are used to determine BCR of each refurbishment option. For each refurbishment option, it is assumed that the capital cost of each option occurs in the first year and that costs and benefits begin to accumulate in the same year (year 0). The use of DCF techniques over long time period (75 years in this study) and consequently the selection of an appropriate discount rate is difficult because there is considerable uncertainty regarding the way in which interest or inflation rates might change in the future (HM Treasury, 2007). For the purpose of this study, a discount rate of 3.5 % was selected in line with the Green Book published by the UK government which describes how the financial investments of a policy, programme or project should be evaluated in the long term to provide the greatest benefits (HM Treasury, 2007).

The benefits (i.e. cost savings) of each refurbishment option are discounted at this rate over its service life but the capital costs associated with each refurbishment option are assumed to remain at today's prices and are not discounted. According to Gaterell and McEvoy (2005b)

capital costs incurred in the future would be discounted in any cost benefit analysis. However, as the aim of this analysis is to highlight the relative cost savings of each refurbishment option under future climate change scenarios, it was decided to remove any variation in the BCR due to changes in capital cost. Rather than being concerned with absolute values, the main purpose is to consider changes in relative BCR.

Similar to the OER analysis, three stages of calculations are considered for BCR analysis. The first stage assumes that no climate change is occurred over the service life of any refurbishment options. Consequently, the net cost savings achieved by each refurbishment option remain constant over its service life. The second stage of the calculation considers the impact of climate changes projected under the low emissions scenario. The third stage considers the impact of climate changes projected under the high emissions scenario.

Results from these stages of calculations are summarised in (**Figures 7.18-7.21)** for the cellular office while results for the open-plan office and the teaching room are summarised in (**Appendix J**).

Results from the first stage of calculations (No climate change scenario) in the cellular office suggest that for the north façade (**Figure 7.18a**), the wall insulation (U-value = 0.35 W/m^{2}K) appears to have the highest BCR (i.e. most economically efficient) compared to the other refurbishment solutions. However, for the south, east and west façades (**Figures 7.19a-7.21a**) the high performance glazing (U-value = 0.7 W/m^{2}K) is the most economically efficient option. The BCR is in favour of the wall insulation (U-value = 0.35W/m^{2}K) for the north façade due to higher savings in heating energy cost and lower cooling energy cost compared to other orientations and refurbishment options.
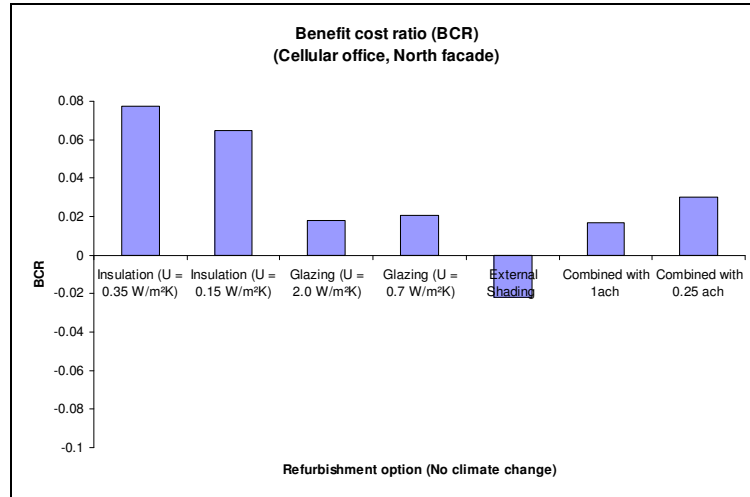
(a) No climate change
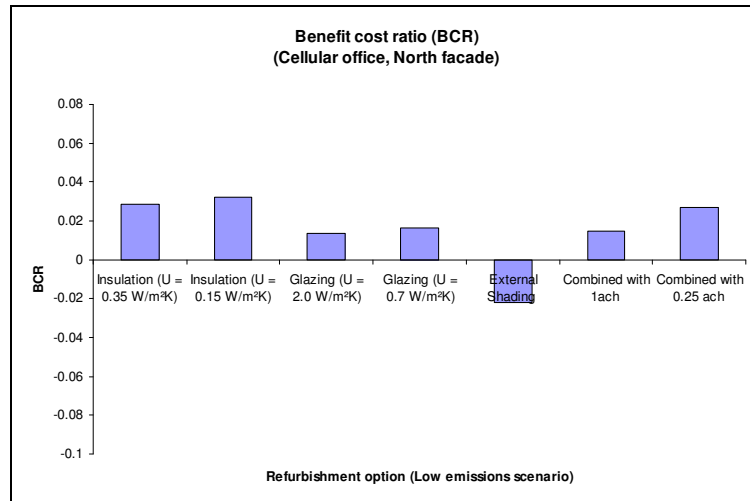
(b) Climate change-Low emissions scenario
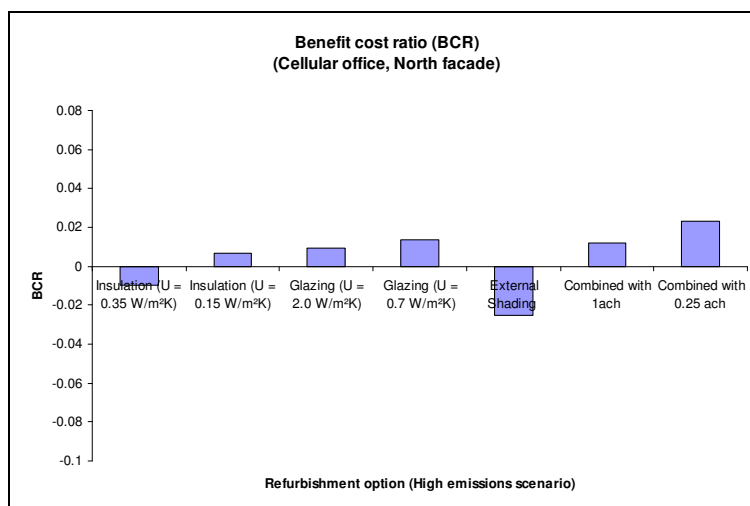
(c) Climate change-High emissions scenario

Figure 7.18 BCR for the north façade of the cellular office
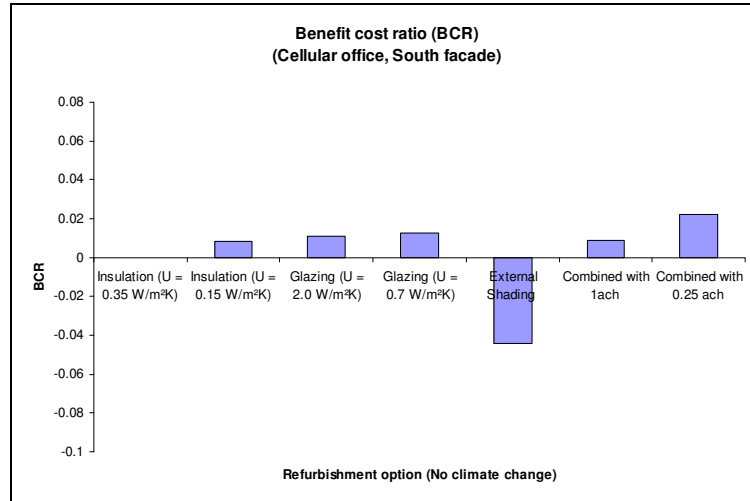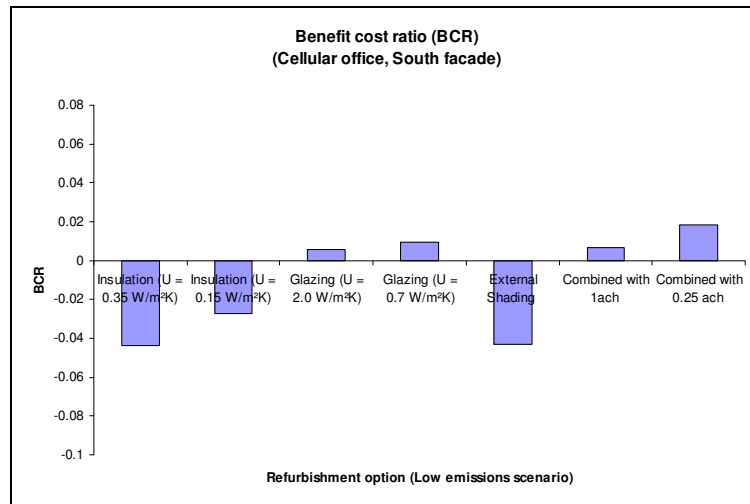
(a) No climate change

(b) Climate change-Low emissions scenario
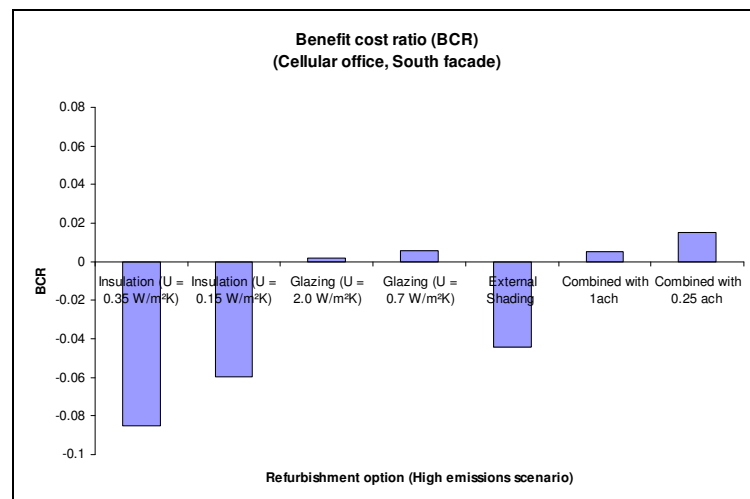
(c) Climate change-High emissions scenario

Figure 7.19 BCR for the south façade of the cellular office
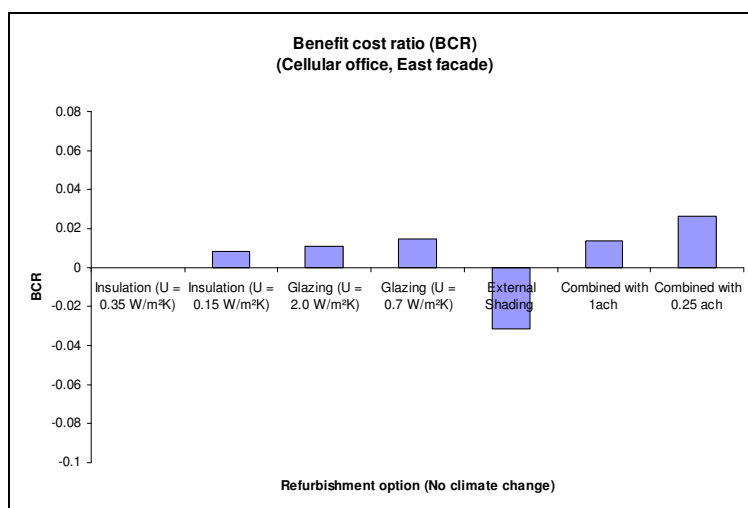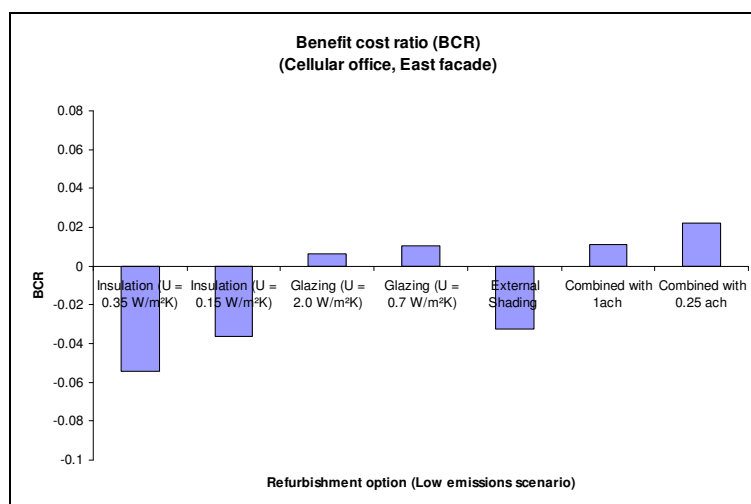
(a) No climate change

(b) Climate change-Low emissions scenario
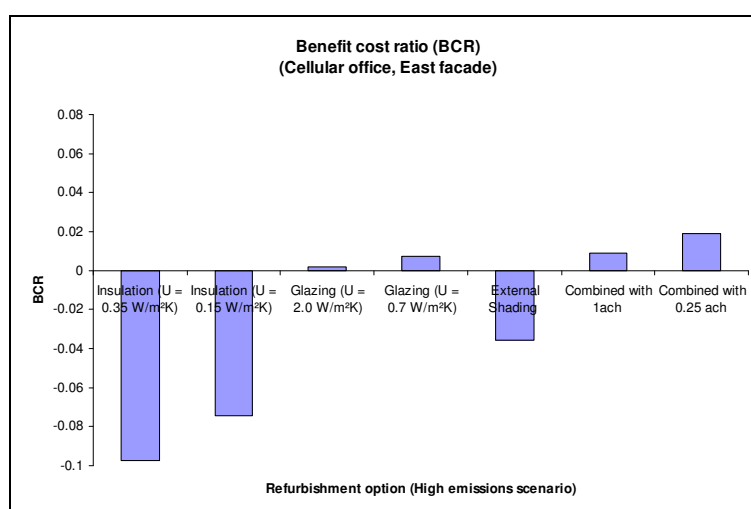
(c) Climate change-High emissions scenario

Figure 7.20 BCR for the east façade of the cellular office
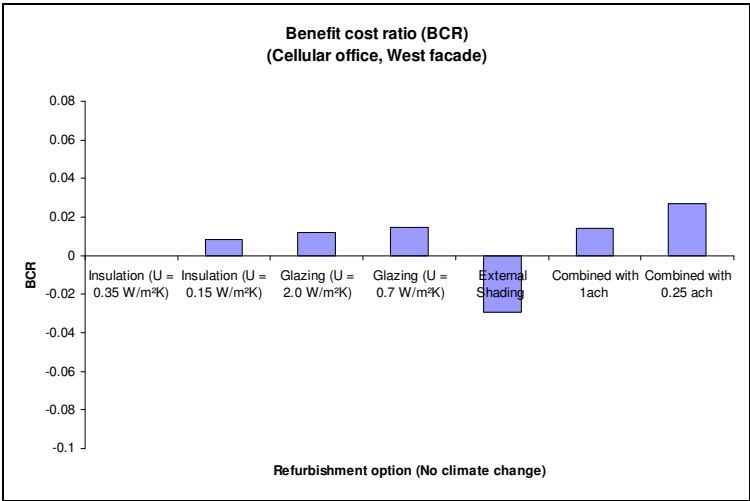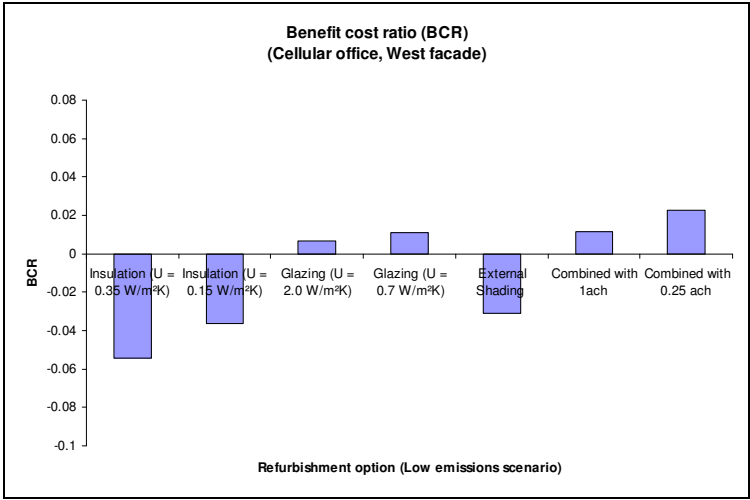
(a) No climate change

(b) Climate change-Low emissions scenario
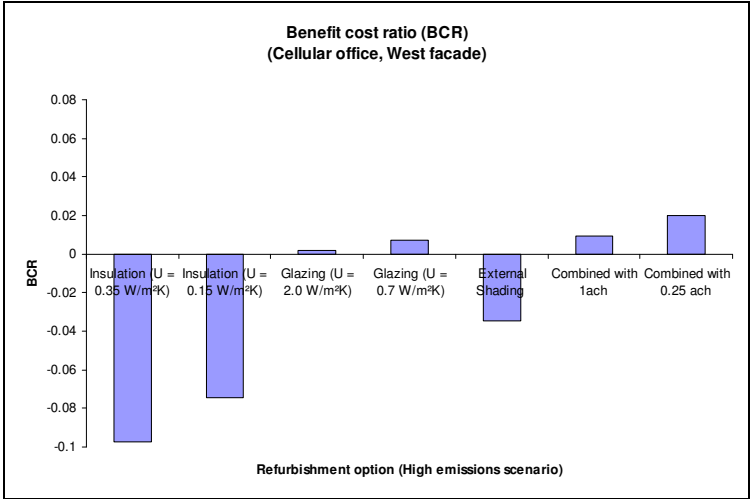
(c) Climate change-High emissions scenario

Figure 7.21 BCR for the west façade of the cellular office

However, for other orientations high performance glazing (U-value = 0.7 W/m^{2}K) as a single refurbishment solution appears to generate the highest savings in energy cost despite the highest capital cost. External shading has the lowest BCR for all orientations and consequently, the least economically efficient single refurbishment solution. 'Combined all with 0.25 ach' is the most economically efficient 'combined all options' compared to 'combined all with 1 ach' option for all orientations.

Results from the second and third stages of calculations suggest that the cost effectiveness of the wall insulation (U-value 0.35 W/m^{2}K and 0.15 W/m^{2}K) for the north façade reduces at a faster rate under low (**Figure 7.18b**) and high emissions scenarios (**Figure 7.18c**) compared to the other refurbishment solutions. The introduction of climate change impacts will change the wall insulation (U-value = 0.35 W/m^{2}K) from being the most economically efficient single refurbishment option to become the least economically efficient option. This can be seen clearly under the high emissions scenario for the south, east and west façades (**Figures 7.19c-7.21c**).

Despite having the lowest capital cost (**Table 7.2**), the changing relationship between reductions in the heating energy costs and increases in the cooling energy costs of the wall insulation (U-value = 0.35 W/m^{2}K and 0.15 W/m^{2}K) has a considerable impact on the net cost savings and therefore on the BCR. This would change the ranking of the refurbishment options based on BCR with climate change impacts when compared to that based on BCR without climate change impacts.

Reductions in BCRs highlight the sensitivity of the cost effectiveness of different refurbishment options to climate variables. The cost effectiveness of the wall insulation (U-value = 0.35 W/m^{2}K and 0.15 W/m^{2}K) is the most sensitive of the refurbishment options to

changes in climate scenario. Such sensitivity results from the valuation of the relatively high cooling energy costs introduced which, when compared to the capital costs begin to reduce the numerator of the BCR equation and consequently reduce the BCR.

The high performance glazing (U-value = 2.0 W/m^{2}K and 0.7 W/m^{2}K) and the 'combined all options' (1 ach and 0.25 ach) are relatively less sensitive to changes in climate scenario than the wall insulation. Despite the higher capital cost [denominator in the BCR equation] for the high performance glazing and the combination of all refurbishment options solutions compared to the wall insulation, the higher net savings in costs over the long time horizon (75 years) [the numerator in the BCR equation], which results from the higher cost savings in both heating and cooling energy, will not significantly change the BCR ratio.

Results for the open-plan office and the teaching room are shown in **Appendix J1** and **Appendix J2** respectively. For the open-plan office (**Appendix J1**), results for both excluding and including climate change impacts suggest that glazing (0.7 W/m^{2}K) has the highest BCR (i.e. most economically efficient option) compared to other single refurbishment solutions. Wall insulation (0.35 W/m^{2}K) has the lowest BCR (i.e. least economically efficient option) for all climate scenarios. 'Combined all with 0.25 ach' has higher BCR (i.e. more economically efficient) compared to 'combined all with 1 ach' for different climate scenarios.

For the teaching room (**Appendix J2**), results for both excluding and including climate change impacts suggest that glazing (0.7 W/m^{2}K) has the highest BCR (i.e. most economically efficient) compared to other single refurbishment solutions. External shading has the lowest BCR. 'Combined all with 0.25 ach' has higher BCR (i.e. more economically efficient) compared to 'combined all with 1 ach' for different climate scenarios.

7.6   The framework

Referring to the AUDE toolkit, previously discussed in **Chapter 4 (Section 4.2.4)**, once refurbishment has been determined to be the most sustainable solution compared to the demolition and rebuild following the filter tool, a comprehensive framework can be developed from this case study (**Figure 7.22**). This developed framework can be considered as complementary to the options appraisal matrix tool by extending its application to consider the impacts of climate change when choosing the most sustainable refurbishment solutions; hence a more holistic method of choosing the best refurbishment solutions. This will give managers within the estates greater confidence about the performance of different suggested refurbishment options under different climate change scenarios. The framework developed from this study shows the ranking of different refurbishment options based on thermal efficiency, environmental impact and cost effectiveness for the cellular office (**Figures 7.23-7.25**), the open-plan office (**Figures 7.26-7.28**) and the teaching room (**Figures 7.29-7.31**) and for different climate scenarios. Figures in parenthesis show the ranking of refurbishment options in terms of different performance criteria (i.e. thermal efficiency, environmental impact and cost effectiveness).

The ranking, for each room and for different performance criteria, takes the average of the results from the four orientations (i.e. north, south, east and west). This framework will assist the policy developers and decision-makers within AUDE in deciding which refurbishment option to invest in based on different performance criteria.

In general, the framework suggests that the most thermally efficient refurbishment options are not necessarily the most environmentally friendly or economically efficient. Inclusion of climate change impacts when assessing the relative environmental impact of different

refurbishment options will change the ranking of these options compared to the assessment

which excludes climate change effects.

```
┌─────────────────────────────────┐
│ Step 1: Use AUDE filter tool to │──────────────┐
│ evaluate the potential for       │              │
│ refurbishment of an existing     │              │
│ building                         │              │
└─────────────────────────────────┘              │
                │                                 │
                ▼                                 ▼
┌─────────────────────────────────┐  ┌────────────────────────┐
│ High potential for refurbishment │  │ Demolition and rebuild │
└─────────────────────────────────┘  └────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Step 2: Use AUDE options         │
│ appraisal matrix to compare      │
│ different refurbishment options/ │
│ No consideration of climate      │
│ change                           │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Step 3: Investigate the potential│
│ impact of climate change for     │
│ different suggested refurbishment │
│ options in terms of thermal       │
│ efficiency, environmental impact  │
│ and cost effectiveness            │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Step 4: Identify the most        │
│ sustainable refurbishment        │
│ solution(s)                      │
└─────────────────────────────────┘
```

Figure 7.22 The suggested framework

Refurbishment as a sustainable solution
(Cellular office)

No climate change

Thermal efficiency

Environmental impact

Cost effectiveness

Thermal efficiency
(6) Insulation (0.35W/m^{2}K)
(5) Insulation (0.15 W/m^{2}K)
(4) Glazing (2.0 W/m^{2}K)
(2) Glazing (0.7 W/m^{2}K)
(7) External shading
(3) Combined with 1.0 ach
(1) Combined with 0.25 ach

Environmental impact
(1) Insulation (0.35W/m^{2}K)
(2) Insulation (0.15 W/m^{2}K)
(5) Glazing (2.0 W/m^{2}K)
(6) Glazing (0.7 W/m^{2}K)
(7) External shading
(4) Combined with 1.0 ach
(3) Combined with 0.25 ach

Cost effectiveness
(3) Insulation (0.35W/m^{2}K)
(2) Insulation (0.15 W/m^{2}K)
(6) Glazing (2.0 W/m^{2}K)
(4) Glazing (0.7 W/m^{2}K)
(7) External shading
(5) Combined with 1.0 ach
(1) Combined with 0.25 ach

Figure 7.23 Summary of the ranking of refurbishment options in the cellular office
(No climate change)

Figure 7.24 Summary of the ranking of refurbishment options in the cellular office
(Climate change-Low emissions scenario)

```
                    ┌─────────────────────────────────────┐
                    │  Refurbishment as a sustainable solution │
                    │           (Cellular office)          │
                    └─────────────────────────────────────┘
                                      │
                                      ▼
                    ┌─────────────────────────────────────┐
                    │          Climate change             │
                    │     High emissions scenario         │
                    └─────────────────────────────────────┘
```

Thermal efficiency	Environmental impact	Cost effectiveness
(6) Insulation (0.35W/m^{2}K)	(6) Insulation (0.35W/m^{2}K)	(7) Insulation (0.35W/m^{2}K)
(5) Insulation (0.15 W/m^{2}K)	(5) Insulation (0.15 W/m^{2}K)	(6) Insulation (0.15 W/m^{2}K)
(4) Glazing (2.0 W/m^{2}K)	(3) Glazing (2.0 W/m^{2}K)	(4) Glazing (2.0 W/m^{2}K)
(2) Glazing (0.7 W/m^{2}K)	(4) Glazing (0.7 W/m^{2}K)	(3) Glazing (0.7 W/m^{2}K)
(7) External shading	(7) External shading	(5) External shading
(3) Combined with 1.0 ach	(2) Combined with 1.0 ach	(2) Combined with 1.0 ach
(1) Combined with 0.25 ach	(1) Combined with 0.25 ach	(1) Combined with 0.25 ach

Figure 7.25 Summary of the ranking of refurbishment options in the cellular office
(Climate change-High emissions scenario)

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┌─────────────────────────────────────┐
│  Refurbishment as a sustainable solution  │
│          (Open-plan office)              │
└─────────────────────────────────────┘
                    │
                    ▼
        ┌─────────────────────┐
        │   No climate change   │
        └─────────────────────┘
```

Thermal efficiency	Environmental impact	Cost effectiveness
(6) Insulation (0.35W/m^{2}K)	(7) Insulation (0.35W/m^{2}K)	(7) Insulation (0.35W/m^{2}K)
(5) Insulation (0.15 W/m^{2}K)	(6) Insulation (0.15 W/m^{2}K)	(6) Insulation (0.15 W/m^{2}K)
(4) Glazing (2.0 W/m^{2}K)	(3) Glazing (2.0 W/m^{2}K)	(4) Glazing (2.0 W/m^{2}K)
(2) Glazing (0.7 W/m^{2}K)	(4) Glazing (0.7 W/m^{2}K)	(3) Glazing (0.7 W/m^{2}K)
(7) External shading	(5) External shading	(5) External shading
(3) Combined with 1.0 ach	(2) Combined with 1.0 ach	(2) Combined with 1.0 ach
(1) Combined with 0.25 ach	(1) Combined with 0.25 ach	(1) Combined with 0.25 ach

Figure 7.26 Summary of the ranking of refurbishment options in the open-plan office
(No climate change)

Refurbishment as a sustainable solution
(Open-plan office)

Climate change
Low emissions scenario

Thermal efficiency	Environmental impact	Cost effectiveness

Thermal efficiency	Environmental impact	Cost effectiveness
(6) Insulation (0.35W/m^{2}K)	(7) Insulation (0.35W/m^{2}K)	(7) Insulation (0.35W/m^{2}K)
(5) Insulation (0.15 W/m^{2}K)	(6) Insulation (0.15 W/m^{2}K)	(6) Insulation (0.15 W/m^{2}K)
(4) Glazing (2.0 W/m^{2}K)	(3) Glazing (2.0 W/m^{2}K)	(4) Glazing (2.0 W/m^{2}K)
(2) Glazing (0.7 W/m^{2}K)	(4) Glazing (0.7 W/m^{2}K)	(3) Glazing (0.7 W/m^{2}K)
(7) External shading	(5) External shading	(5) External shading
(3) Combined with 1.0 ach	(2) Combined with 1.0 ach	(2) Combined with 1.0 ach
(1) Combined with 0.25 ach	(1) Combined with 0.25 ach	(1) Combined with 0.25 ach

Figure 7.27 Summary of the ranking of refurbishment options in the open-plan office
(Climate change-Low emissions scenario)

Figure 7.28 Summary of the ranking of refurbishment options in the open-plan office
(Climate change-High emissions scenario)

```
                    ┌─────────────────────────────────┐
                    │ Refurbishment as a sustainable solution │
                    │          (Teaching room)        │
                    └─────────────────────────────────┘
                                     │
                                     ▼
                    ┌─────────────────────────────────┐
          ┌─────────┤         No climate change        ├─────────┐
          │         └─────────────────────────────────┘         │
          ▼                        ▼                             ▼
┌──────────────────┐   ┌──────────────────────┐   ┌──────────────────┐
│ Thermal efficiency │   │ Environmental impact │   │ Cost effectiveness │
└──────────────────┘   └──────────────────────┘   └──────────────────┘
          │                        │                             │
          ▼                        ▼                             ▼
```

Thermal efficiency	Environmental impact	Cost effectiveness
(4) Insulation (0.35W/m²K)	(6) Insulation (0.35W/m²K)	(6) Insulation (0.35W/m²K)
(3) Insulation (0.15 W/m²K)	(4) Insulation (0.15 W/m²K)	(4) Insulation (0.15 W/m²K)
(6) Glazing (2.0 W/m²K)	(5) Glazing (2.0 W/m²K)	(5) Glazing (2.0 W/m²K)
(5) Glazing (0.7 W/m²K)	(3) Glazing (0.7 W/m²K)	(3) Glazing (0.7 W/m²K)
(7) External shading	(7) External shading	(7) External shading
(2) Combined with 1.0 ach	(2) Combined with 1.0 ach	(2) Combined with 1.0 ach
(1) Combined with 0.25 ach	(1) Combined with 0.25 ach	(1) Combined with 0.25 ach

Figure 7.29 Summary of the ranking of refurbishment options in the teaching room
(No climate change)

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                    ┌─────────────────────────────────┐
                    │ Refurbishment as a sustainable   │
                    │ solution (Teaching room)         │
                    └─────────────────────────────────┘
                                     │
                                     ▼
                    ┌─────────────────────────────────┐
                    │      Climate change              │
                    │      Low emissions scenario      │
                    └─────────────────────────────────┘
```

Thermal efficiency	Environmental impact	Cost effectiveness
(4) Insulation (0.35W/m^{2}K)	(6) Insulation (0.35W/m^{2}K)	(6) Insulation (0.35W/m^{2}K)
(3) Insulation (0.15 W/m^{2}K)	(5) Insulation (0.15 W/m^{2}K)	(4) Insulation (0.15 W/m^{2}K)
(6) Glazing (2.0 W/m^{2}K)	(4) Glazing (2.0 W/m^{2}K)	(5) Glazing (2.0 W/m^{2}K)
(5) Glazing (0.7 W/m^{2}K)	(3) Glazing (0.7 W/m^{2}K)	(3) Glazing (0.7 W/m^{2}K)
(7) External shading	(7) External shading	(7) External shading
(2) Combined with 1.0 ach	(2) Combined with 1.0 ach	(2) Combined with 1.0 ach
(1) Combined with 0.25 ach	(1) Combined with 0.25 ach	(1) Combined with 0.25 ach

Figure 7.30 Summary of the ranking of refurbishment options in the teaching room
(Climate change-Low emissions scenario)

```
┌─────────────────────────────────────┐
│   Refurbishment as a sustainable solution │
│             (Teaching room)              │
└─────────────────────────────────────┘
                    │
                    ▼
        ┌───────────────────────┐
        │     Climate change       │
        │ High emissions scenario  │
        └───────────────────────┘
```

Thermal efficiency	Environmental impact	Cost effectiveness
(4) Insulation (0.35W/m^{2}K)	(6) Insulation (0.35W/m^{2}K)	(6) Insulation (0.35W/m^{2}K)
(3) Insulation (0.15 W/m^{2}K)	(5) Insulation (0.15 W/m^{2}K)	(5) Insulation (0.15 W/m^{2}K)
(6) Glazing (2.0 W/m^{2}K)	(4) Glazing (2.0 W/m^{2}K)	(4) Glazing (2.0 W/m^{2}K)
(5) Glazing (0.7 W/m^{2}K)	(3) Glazing (0.7 W/m^{2}K)	(3) Glazing (0.7 W/m^{2}K)
(7) External shading	(7) External shading	(7) External shading
(2) Combined with 1.0 ach	(2) Combined with 1.0 ach	(2) Combined with 1.0 ach
(1) Combined with 0.25 ach	(1) Combined with 0.25 ach	(1) Combined with 0.25 ach

Figure 7.31 Summary of the ranking of refurbishment options in the teaching room
(Climate change-High emissions scenario)

However, the framework suggested in this study is related to a specific building (Muirhead Tower), which is a tower block. This type of HE buildings is considered the most vulnerable type to climate change (Bahaj et al., 2008). Moreover, the types of rooms selected within the tower (cellular office, open-plan research office and teaching room) are the most energy intensive in a typical HE building (**Figure 4.5**) page 80. Results of heating, cooling demands and their associated CO_2 emissions are likely to be at the upper end of what can be expected for this era and construction type of HE buildings. It is likely that repeating the same analysis on different HE building typologies will not significantly alter the general results outlined above. For instance, some HE buildings typologies might have rooms with smaller glazing ratio (similar to the teaching room discussed in this case study) and therefore result in lowering the heating, cooling demand and the associated CO_2 and the capital costs of refurbishment options (e.g. double, triple glazing). However, the ranking of different suggested refurbishment solutions are likely to be similar to those in the teaching room. As a result, the general findings are unlikely to be different for other HE buildings of a similar era of construction.

It is likely that the development in understanding of climate change uncertainty, changing in future energy prices and the intensity of CO_2 emissions from different fuel types could alter the results from this analysis and therefore, the ranking of different refurbishment options. Consequently, it is vitally important that the adopted policy and investment decision-making process within AUDE remains a dynamic and proactive procedure; able to respond to different developments and shape their policies and decisions accordingly. The framework developed in this study could be used to evaluate future scenarios (e.g. future predictions for climate change, uncertainties in energy prices).

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8.1   Introduction

The extensive literature review discussed in **Chapters 2-5** has been used to systematically evaluate the potential contribution of the built environment in general, and HE buildings in particular, to reducing the environmental impact over their lifecycle, whilst improving occupants' comfort and ensuring economic viability. However, as discussed in **Chapter 3**, climate change poses a serious threat to the capacity of these buildings to deliver thermal comfort and must be considered in any plan to reduce environmental and economic impacts. Therefore, any refurbishment strategies designed to make HE buildings more resilient and adaptable must consider climate change impacts. In **Chapter 6**, Muirhead Tower, at the University of Birmingham, in the UK, was chosen as the HE case study building. Thermal simulation was undertaken to investigate the likely impacts of climate change on thermal comfort levels in typical elements of Muirhead Tower and identify which refurbishment options are likely to remain effective under the recent set of future climate change scenarios. Results from thermal simulation are analysed and their significance is discussed in **Chapter 7**. This chapter draws together the conclusions of this study and gives recommendations and outlines the scope for future investigations.

8.2   Conclusions

Achieving sustainable development requires humankind to live within the limits of the environment's capacity; provide resources for human activities and subsequently absorb the pollution and waste that these activities generate. Sustainable construction, as a necessary contributing element of sustainable development in the built environment, aims to reduce the environmental impact of a building over its entire lifecycle, whilst improving its comfort and the safety of its occupant and ensuring economic viability. As a consequence of increased global energy demands serious environmental impacts (pollution, CO_2 emissions and climate change) are becoming evident. Moreover, fossil fuels are becoming increasingly finite (and unaffordable) leading to a pressing need for the built environment to become more energy efficient. Therefore the adoption of a passive design approach, which takes into consideration climate change and its impacts, will ensure that buildings remain resilient; healthy; affordable and resource efficient.

HEIs have a fundamental role in contributing to the agenda for sustainable development and the significance of the performance of the HEI estate has been acknowledged. Encouraged by impending legislation, rising energy costs and tightening of building regulations, HEIs are beginning to adopt sustainable approaches. Considerable sums of money are being spent on refurbishing parts of the post-war HEI estate, much of which was built to thermal standards far lower than those expected today. Clearly, if HEIs are to realise their opportunity to contribute to sustainable development agenda it is essential that the overall performance of the refurbishment strategies adopted within the estate is evaluated over their whole life.

AUDE has developed a toolkit that enables the relative sustainability of refurbishment options within HEIs to be evaluated systematically. The AUDE toolkit represents an essential first step towards addressing the key issues that need to be taken into consideration when identifying the most sustainable refurbishment options for higher education building stock. However, it does not consider the potential impact of uncertainties regarding future climate conditions. Any change in prevailing climate conditions will undoubtedly impact the thermal efficiency within these refurbished estates, and, therefore, the long term sustainability of the building. Assets within a HEI estate have long design lives (80 years or more is not uncommon) and therefore any systematic evaluation of a given refurbishment option such as that developed by AUDE necessarily needs to consider the impact of future climate change to ensure it is sustainable and effective over its whole life time. This work has extended the AUDE toolkit to consider the potential impacts of climate change on the ability of different refurbishment options to provide the appropriate comfort conditions without incurring excessive energy use, cost and CO_2 emissions. This is considered to be a more comprehensive toolkit for the assessment of a given refurbishment solutions with the HE building stock.

Analysis of a case study building, using thermal modelling, indicates that overheating is likely to occur in similar HE buildings that rely solely on natural ventilation for cooling even in the present day conditions and increasingly so under climate change conditions. The analysis revealed also that temperature increases resulting from climate change will cause significant reductions in total heating requirements and increases in total cooling requirements for HE buildings. The amount of the reduction in the heating energy or the increase in the cooling energy depends mainly on the temperature change in the climate

scenario, the calculated sensitivity of the building stock to warming, building type, orientation and the adjustments allowed in the building stock over time.

An evaluation of the performance of given refurbishment options applied to the case study building under different future climate change scenarios suggest that their impact could be considerable. The modelling results suggest that while it would be difficult as the climate warms to meet the thermal performance targets considered here using passive refurbishment options alone, refurbishment options will generally result in reduced net annual energy consumption compared to the building that had not been refurbished. A well insulated refurbished HE building will result in lower heating energy demand but higher number of hours above comfort level during summer and thus increased cooling demand accordingly, particularly for rooms with high level of occupancy and equipment usage (Open-plan rooms and teaching rooms). For those rooms, the high internal heat gain from occupants and equipment are an important contributor to overheating. The high fresh air ventilation rates required to maintain good air quality means that as the external air temperature increases, it becomes increasingly difficult to achieve comfort standards through ventilation by ambient air and the use of passive refurbishment options alone. The results suggest that a move towards a mixed mode approach may be the most practical way to achieve thermal performance targets. The warming climate stresses the need to limit internal heat gains to rooms as far as possible since it has been shown in this study to significantly contribute to summertime thermal discomfort. This means reducing the density of occupants or the power output of lights and machines by using more energy efficient equipment.

While thermal comfort expectations are unlikely to be achieved by relying solely on passive refurbishment options, the increase in cooling energy demand will be less than if no refurbishment options were applied. Moreover, in the UK, since the heating season is much longer than the cooling season the annual net energy consumption as a result of refurbishment will be less under future climate. The increase in cooling energy will be offset by the reduction in the heating energy. However, it is worth noting that these results were based on the current carbon intensity of gas and electricity, which are likely to change in the future and the balance will change accordingly.

A framework has been developed from this study, which is considered as a complementary to the AUDE toolkit by taking climate change impacts into consideration missing in the original toolkit. This framework should be integrated into the AUDE toolkit and it will assist decision makers within AUDE in choosing the most effective and sustainable refurbishment option depending on different performance criteria (thermal efficiency, environmental impact and cost effectiveness). For the case study building considered here and in terms of thermal efficiency, triple glazing window (U-value of 0.70 W/m^{2}K) is the best single refurbishment solution in the cellular and open-plan offices while wall insulation option (U-value = 0.15 W/m^{2}K) is the best single refurbishment option in the teaching room for the scenarios considered. However, adopting a combination of refurbishment solutions to achieve 0.25 ach is the most effective combined solution. External shading is the least effective refurbishment solution in terms of thermal efficiency. Climate change is unlikely to change the ranking of different refurbishment options in terms of thermal efficiency. However, in terms of environmental impact (i.e. CO_2 emissions), climate change impacts are likely to change the ranking of different refurbishment options depending on the considered scenario. In

the cellular office and under low emissions scenario, wall insulation option (U-value = 0.15 W/m^{2}K) as a single refurbishment solution has the lowest environmental impact. Under high emissions scenario, double glazing (U-value = 2.0 W/m^{2}K) has the lowest environmental impact. In the open-plan office and under low emissions scenario, double glazing (U-value = 2.0 W/m^{2}K) as a single refurbishment solution has the lowest environmental impact. Under high emissions scenario, triple glazing (U-value = 0.7 W/m^{2}K) has the lowest environmental impact. However, in the teaching room and under low and high emissions scenario, triple glazing (U-value = 0.7 W/m^{2}K) has the lowest environmental impact. A combination of all refurbishment solutions to achieve 0.25 ach has the lowest environmental impact as a combined solution for all rooms under low and high emissions scenarios while external shading has the highest environmental impact for all rooms. In terms of cost effectiveness, triple glazing (U-value = 0.7 W/m^{2}K) as a single refurbishment solution is the most economically efficient option for all rooms and under low and high emissions scenario. A combination of all refurbishment solutions as a combined option to achieve 0.25 ach is the most economically efficient option for all rooms and under low and high emissions scenarios. External shading is the least economically efficient option. To choose a compromise solution, which meets all performance criteria (i.e. thermal efficiency, environmental impact and cost effectiveness) a 'combined all refurbishment solutions' option is suggested.

Results from this study highlight that for the case study building, suggested refurbishment options based on current normal market energy prices, CO_2 intensity and today's climate are likely to deliver savings and remain effective under significant levels of climate change uncertainties. The developed framework can assist decision-makers and policy development within the HEIs on selecting the most thermally efficient, cost

effective and less environmentally impact refurbishment solutions. Moreover, this framework can serve as a constructive model for other building managers in other sectors when preparing adaptive actions and refurbishment strategies for their stock in the face of future climate change.

8.3   Future work

The results presented here relate to elements of a particular HE building (Muirhead Tower) for which reasonable assumptions have been made for variables such as heating, schedules, occupancy patterns, internal heat gain level, opening windows, thermal mass, air infiltration, building location, orientations and set point. Further research is needed to better understand the influence of various design variables. Results have shown that internal gains are a significant component of space heat gains. The energy consumption of lighting within HE buildings can be significant if not managed correctly. Lighting energy in this analysis was assumed to be constant throughout the year which is not what normally occurs in real situations (i.e. during summer season [June-September], lighting energy consumption is less than during winter season [October-May] due to longer hours of daylight). The main concern in this thesis was the impact of climate change on the likely refurbishment options in delivering the required heating and cooling load and thermal comfort. However, there is also a considerable impact of applying different refurbishment options, particularly shading, on lighting energy which needs to be investigated in further research.

In this analysis it was assumed that there will not be any significant changes in occupant thermal comfort expectations over time. However, recent thermal comfort studies show that it is not really the case. Therefore, the future occupant thermal comfort expectation and personal adaptation to future climate need to be well understood for future studies.

The valuation of the social costs of carbon (SCC) [i.e. the estimate of the monetary value of the damage done by anthropogenic CO_2 emissions] is constantly evolving with new research continually being funded by the UK government and its agencies (HM Treasury, 2007). A paper published by the UK government in 2007 called 'the social cost of carbon and the shadow price of carbon' suggested £19 per tonne of CO_2 [within a range of £10to £38 per tonne of CO_2] as an illustrative estimate for the damage cost of CO_2 emissions (DEFRA, 2007b). This paper also suggested that these figures are likely to increase in real terms by £ 0.27 per tonne of CO_2 per year to reflect the increasing costs of CO_2 emissions over time. Clearly, estimating such cost is highly uncertain, however, the inclusion of SCC is likely   to change the rank of preference of different options suggested in any policy development or decision making process. Due to the time restriction, SCC was not considered in this study but it would be an interesting area for future research.

Moreover, the analyses undertaken here were based on UKCIP02 scenarios and the associated weather files generated based on these scenarios and using the morphing methodology. Currently, there are differences in climate sensitivity among these models as well as differences in methodological emphasis. Long terms conclusions are still difficult due to uncertainties not only in the future climate, but also in the future economic and population growth, technological changes, social and cultural change that could shape policies and actions, individually and institutionally. However, these uncertainties do not remove the responsibility to take part in preparing for them or excuse us as accountable shapers of the future.

It is likely that these future developments will press the need for better understanding and revising of the methodology used to assess climate change particularly with the recent release of UKCIP09 projections at the time of writing this thesis.

This new probabilistic climate change projections (UKCIP09) will provide a major motive for the development of methodologies and data for building design and simulations and allow better risk assessments to be investigated for different scenarios. Therefore, these probabilistic scenarios will be more robust because it can describe the degree of uncertainty in the scenario in probabilistic terms, allowing the investigation of the sensitivity of HE stocks to climate change. Moreover, it helps to investigate the potential impacts of projected climate change uncertainties on the ability of different refurbishment options to deliver anticipated indoor comfort conditions. Results and conclusions based on them about the potential effects can be offered with a higher level of confidence. This will ensure that even under climate change impacts, HE buildings will continue to function safely, comfortably, cost effectively and without excessive need for energy-intensive and high environmental impact refurbishment options.

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APPENDICES

Appendix A: Predicted hours of exceedance of operative temperature of 28°C for the Open-plan office and the Teaching room for different refurbishment options and for different orientation under the Birmingham DSYs for the present-day (2005) and for the UKCIP02 low and high emissions scenarios

A1: Open-plan office

(Open-plan office, South facade)

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

(Open-plan office, East facade)

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

(Open-plan office, West facade)

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Y-axis: % Occupied hours above 28 °C

X-axis: Climate Change Scenario

A2: Teaching Room

(Teaching room, North facade)

(Teaching room, South facade)

(Teaching room, East facade)

Legend:
- □ As Built
- ■ Insulation (U = 0.35 W/m²K)
- □ Insulation (U = 0.15 W/m²K)
- ■ Glazing (U = 2.0 W/m²K)
- ■ Glazing (U = 0.7 W/m²K)
- ■ External Shading
- □ Combined with 1ach
- ■ Combined with 0.25 ach

(Teaching room, West facade)

Legend:
- □ As Built
- ■ Insulation (U = 0.35 W/m²K)
- □ Insulation (U = 0.15 W/m²K)
- ■ Glazing (U = 2.0 W/m²K)
- ■ Glazing (U = 0.7 W/m²K)
- ■ External Shading
- □ Combined with 1ach
- ■ Combined with 0.25 ach

Appendix B: Heating loads under low and high emission scenarios for different orientations of the open-plan office and the teaching room

B1: Open-plan office

Heating load (Open-plan office, North) — Low emissions scenario

Heating load (Open-plan office, North) — High emissions scenario

Heating load (Open-plan office, South)

Low emissions scenario

Legend: As Built · Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Heating load (Open-plan office, South)

High emissions scenario

Legend: As Built · Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Heating load (Open-plan office, East)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Heating load (Open-plan office, East)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Heating load (Open-plan office, West)

Low emissions scenario

Legend: As Built; Insulation (U = 0.35 W/m²K); Insulation (U = 0.15 W/m²K); Glazing (U = 2.0 W/m²K); Glazing (U = 0.7 W/m²K); External Shading; Combined with 1ach; Combined with 0.25 ach

Heating load (Open-plan office, West)

High emissions scenario

Legend: As Built; Insulation (U = 0.35 W/m²K); Insulation (U = 0.15 W/m²K); Glazing (U = 2.0 W/m²K); Glazing (U = 0.7 W/m²K); External Shading; Combined with 1ach; Combined with 0.25 ach

B2: Teaching room

Heating load (Teaching room, North)
Low emissions scenario

Heating load (Teaching room, North)
High emissions scenario

Heating load (Teaching room, South)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Heating load (Teaching room, South)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Heating load (Teaching room, East)

Low emissions scenario

Heating load (Teaching room, East)

High emissions scenario

Heating load (Teaching room, West)

Low emissions scenario

Legend: As Built · Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Heating load (Teaching room, West)

High emissions scenario

Legend: As Built · Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Appendix C: Cooling loads under low and high emission scenarios for different orientations of the open-plan office and the teaching room

C1: Open-plan room

Cooling load (Open-plan office, South)

Low emissions scenario

Cooling load (Open-plan office, South)

High emissions scenario

Cooling load (Open-plan office, East)

Cooling load (Open-plan office, East)

Cooling load (Open-plan office, West)

Low emissions scenario

Legend: As Built, Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Cooling load (Open-plan office, West)

High emissions scenario

Legend: As Built, Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

C2: Teaching room

Cooling load (Teaching room, North) — Low emissions scenario

Cooling load (Teaching room, North) — High emissions scenario

Cooling load (Teaching room, South)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Cooling load (Teaching room, South)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Cooling load (Teaching room, East)

Low emissions scenario

Legend: As Built · Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Cooling load (Teaching room, East)

High emissions scenario

Legend: As Built · Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Cooling load (Teaching room, West)

Cooling load (Teaching room,West)

Appendix D: Total energy demand under low and high emission scenarios for different orientations of the open-plan office and the teaching room
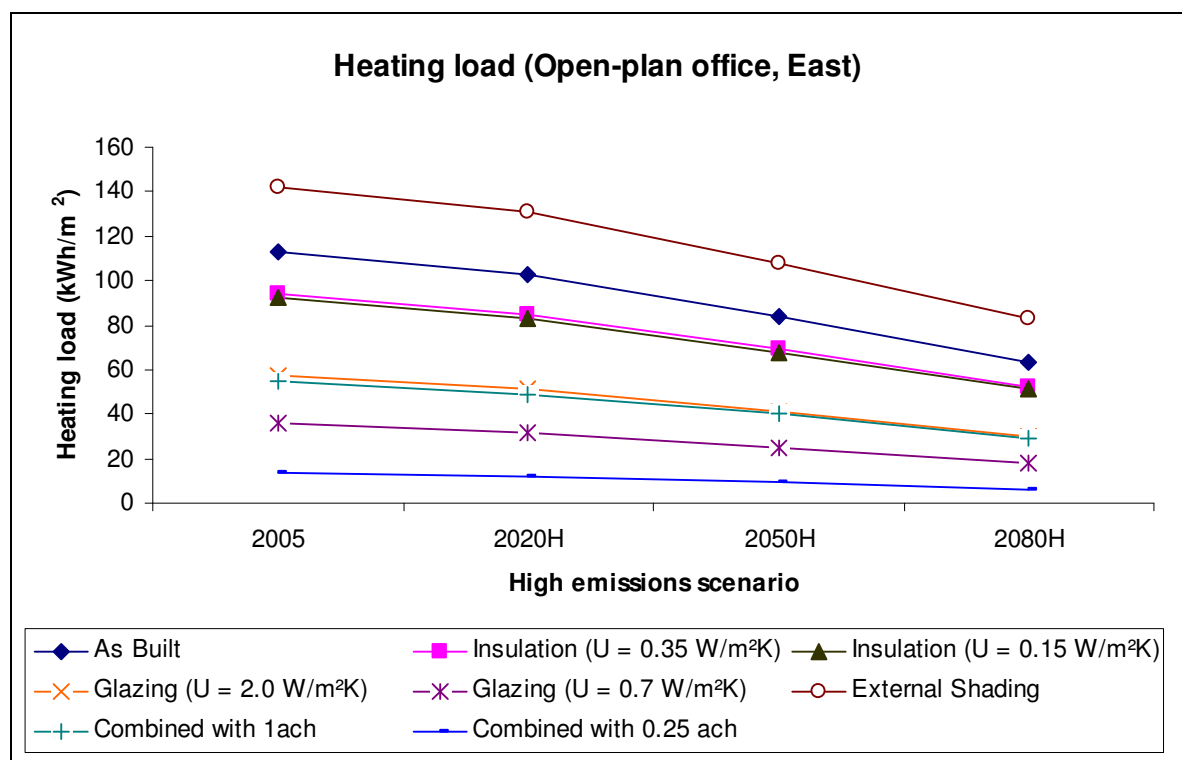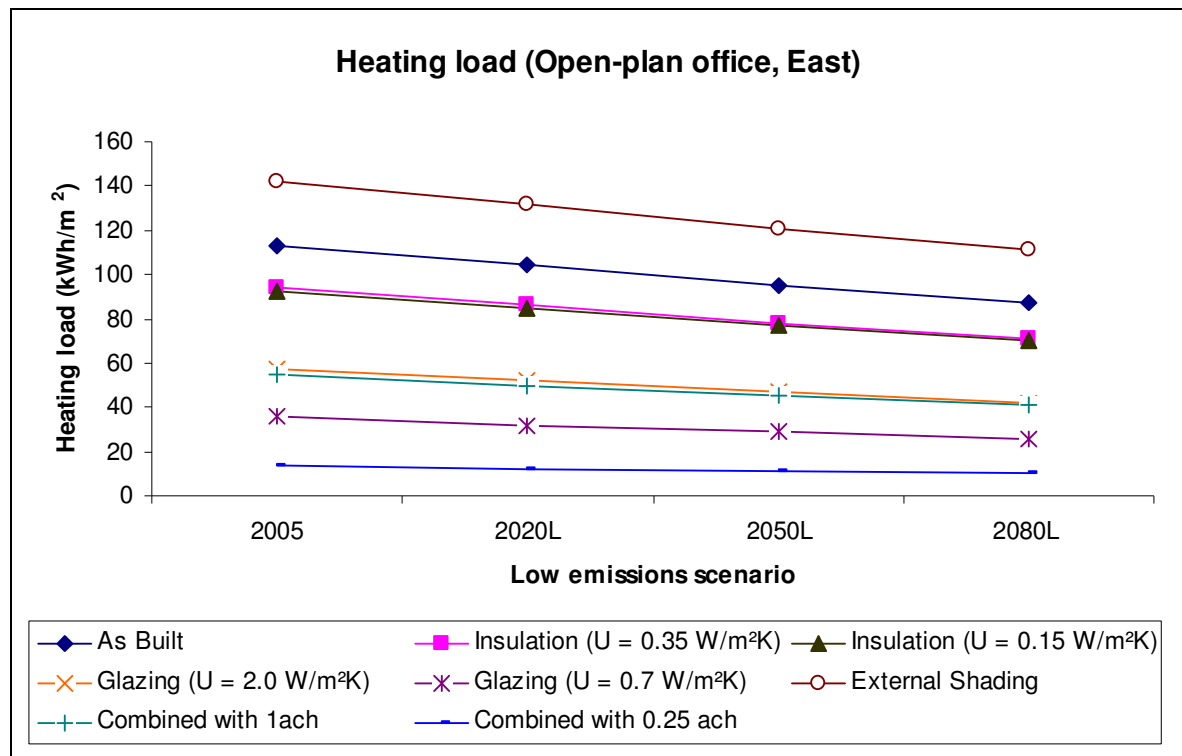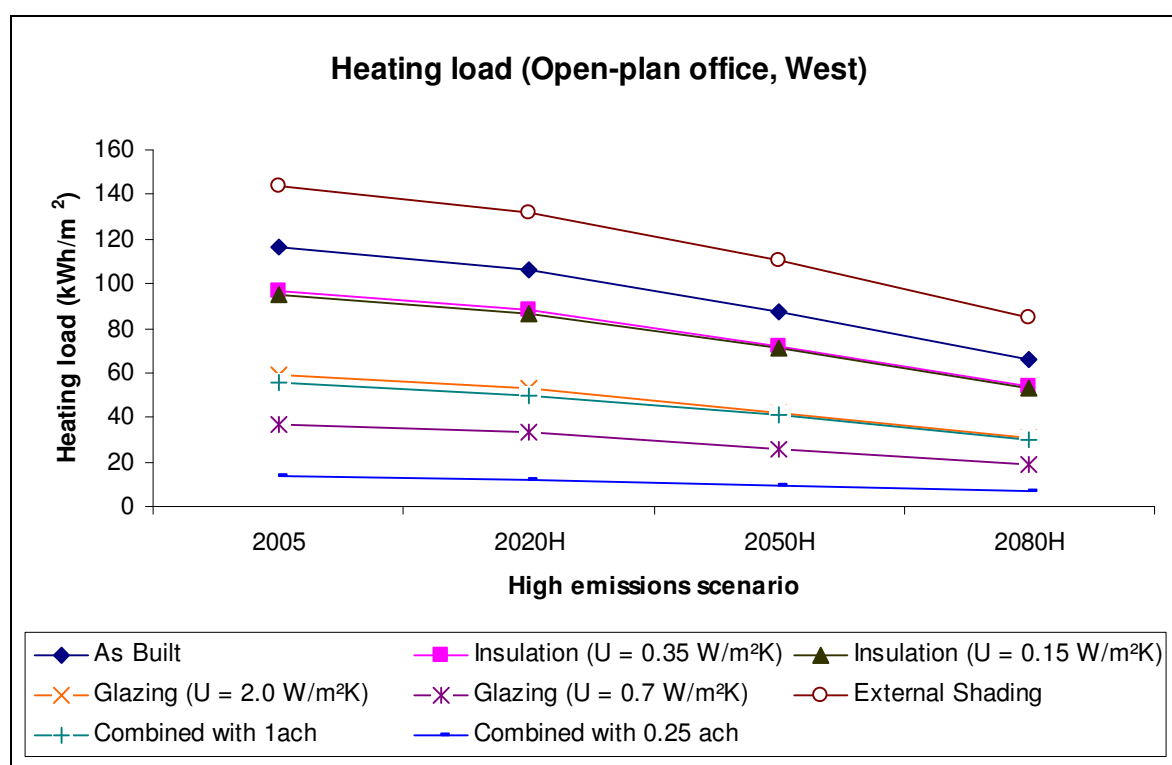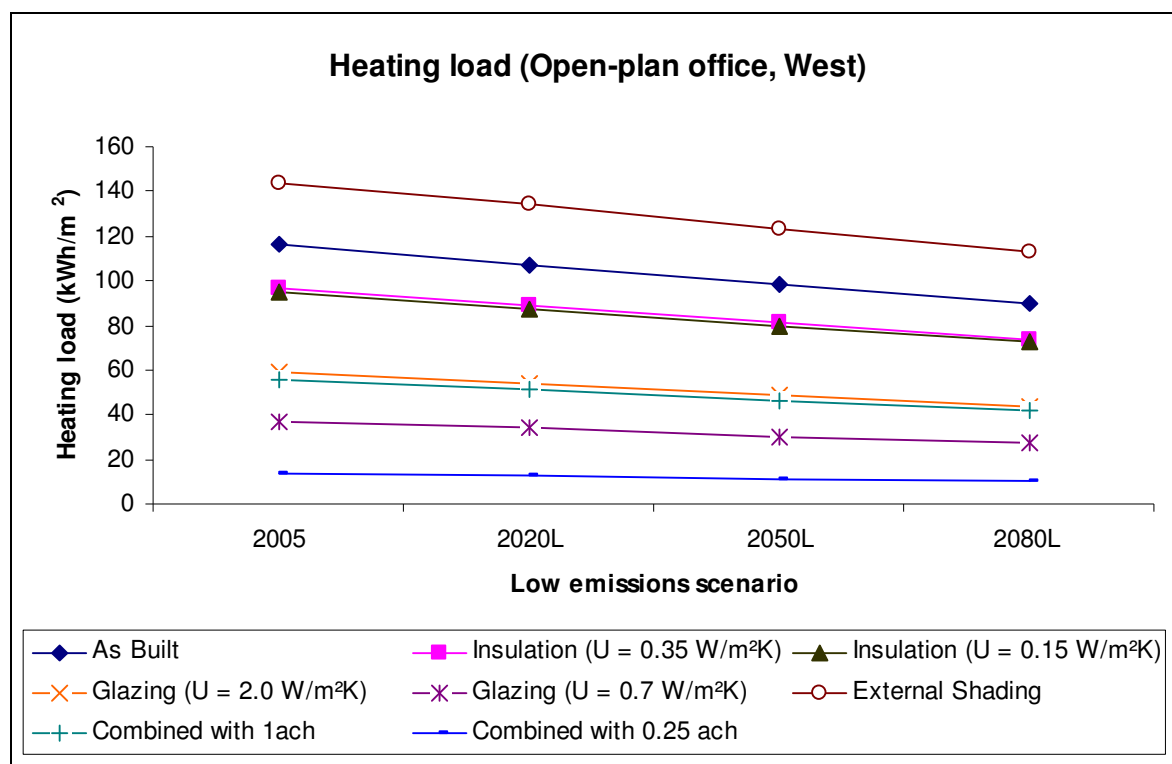
D1: Open-plan office

Total energy demand (Open-plan office, North)

Total energy demand (Open-plan office, North)

Total energy demand (Open-plan office, South)

Low emissions scenario

Legend:
- ◆ As Built
- ■ Insulation (U = 0.35 W/m²K)
- ▲ Insulation (U = 0.15 W/m²K)
- ✕ Glazing (U = 2.0 W/m²K)
- ✳ Glazing (U = 0.7 W/m²K)
- ○ External Shading
- + Combined with 1ach
- — Combined with 0.25 ach

Total energy demand (Open-plan office, South)

High emissions scenario

Legend:
- ◆ As Built
- ■ Insulation (U = 0.35 W/m²K)
- ▲ Insulation (U = 0.15 W/m²K)
- ✕ Glazing (U = 2.0 W/m²K)
- ✳ Glazing (U = 0.7 W/m²K)
- ○ External Shading
- + Combined with 1ach
- — Combined with 0.25 ach

Total energy demand (Open-plan office, East)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total energy demand (Open-plan office, East)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total energy demand (Open-plan office, West)

Total energy demand (Open-plan office, West)

D2: Teaching room

Total energy demand (Teaching room, North)

Low emissions scenario

Legend: As Built; Insulation (U = 0.35 W/m²K); Insulation (U = 0.15 W/m²K); Glazing (U = 2.0 W/m²K); Glazing (U = 0.7 W/m²K); External Shading; Combined with 1ach; Combined with 0.25 ach

Total energy demand (Teaching room, North)

High emissions scenario

Legend: As Built; Insulation (U = 0.35 W/m²K); Insulation (U = 0.15 W/m²K); Glazing (U = 2.0 W/m²K); Glazing (U = 0.7 W/m²K); External Shading; Combined with 1ach; Combined with 0.25 ach

Total energy demand (Teaching room, South)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total energy demand (Teaching room, South)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total energy demand (Teaching room, East)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total energy demand (Teaching room, East)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total energy demand (Teaching room, West)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total energy demand (Teaching room, West)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
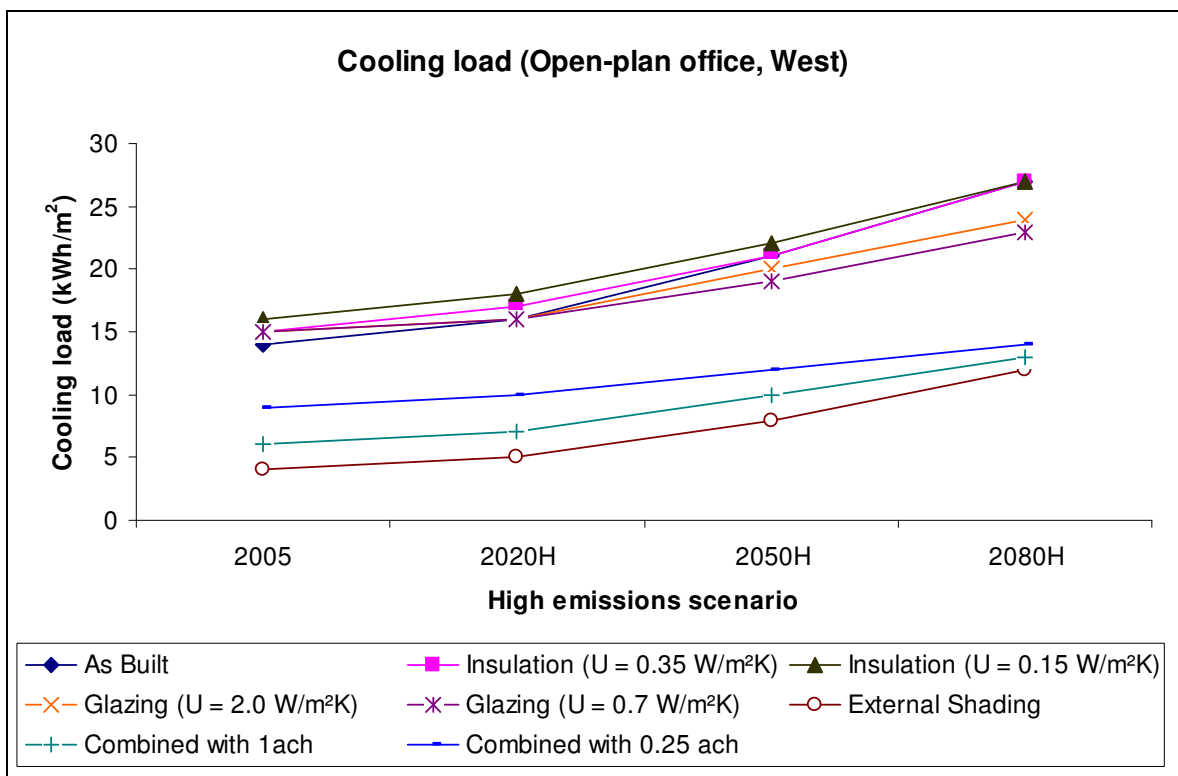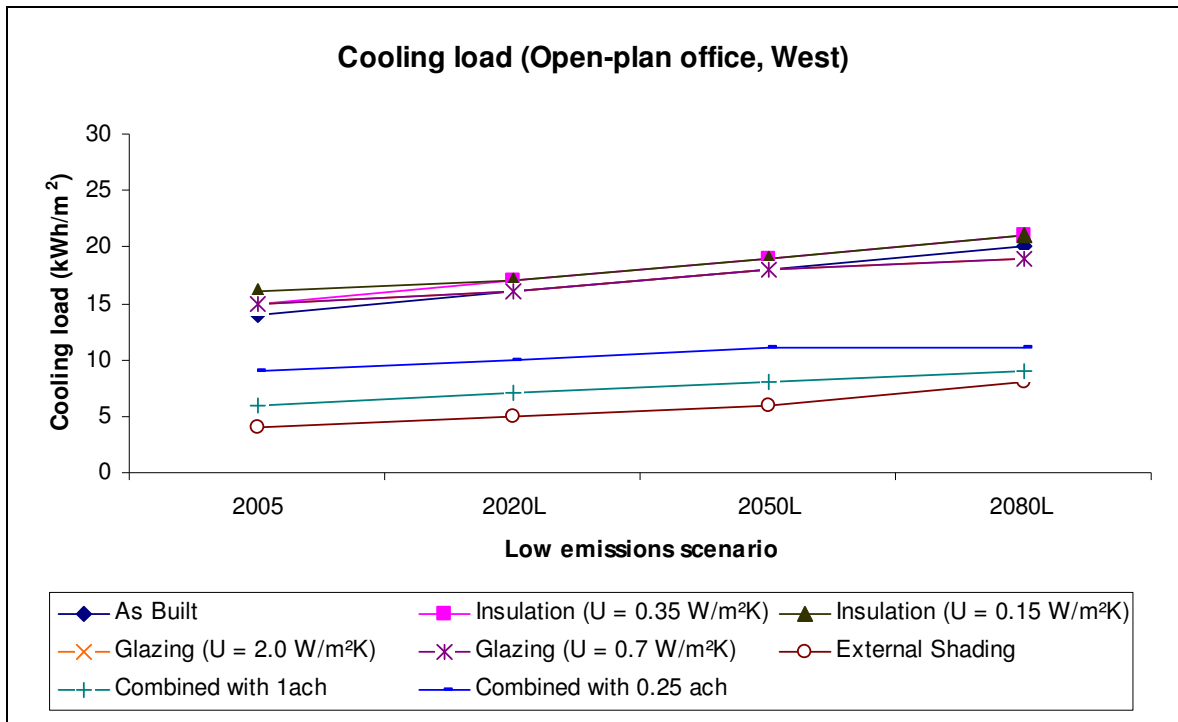- Combined with 1ach
- Combined with 0.25 ach

Appendix E: Total CO₂ emissions under low and high emission scenarios for different orientations of the open-plan office and the teaching room
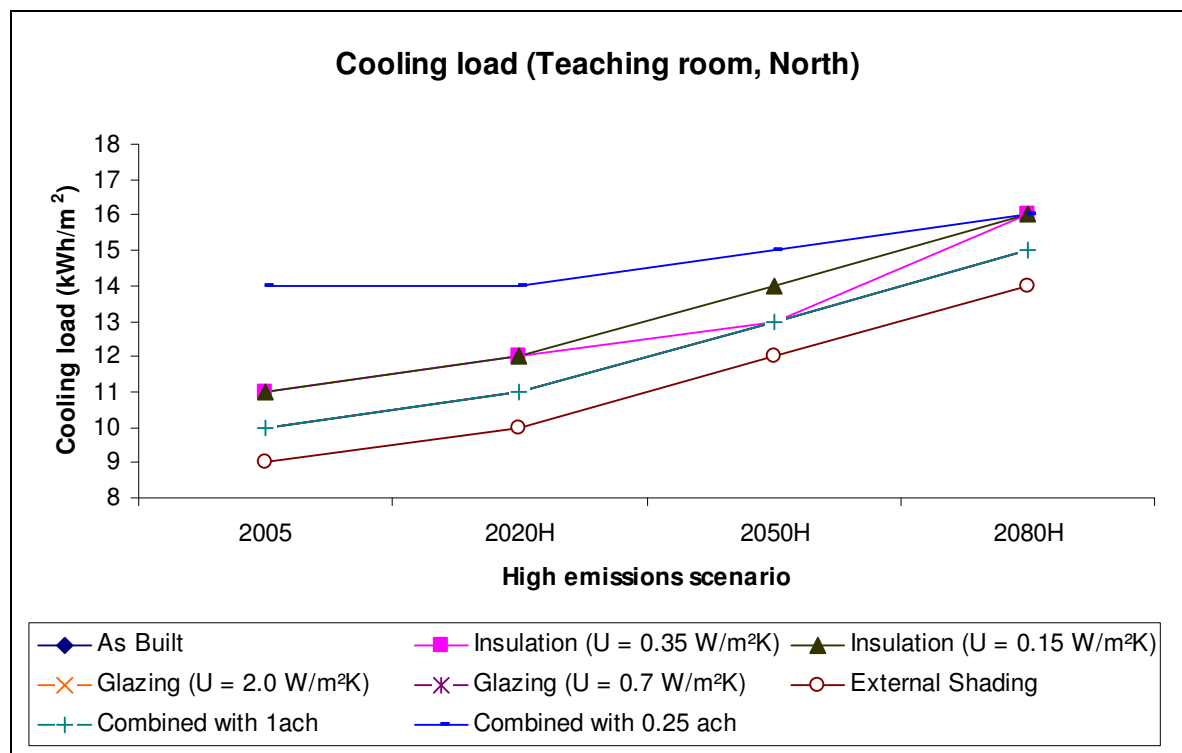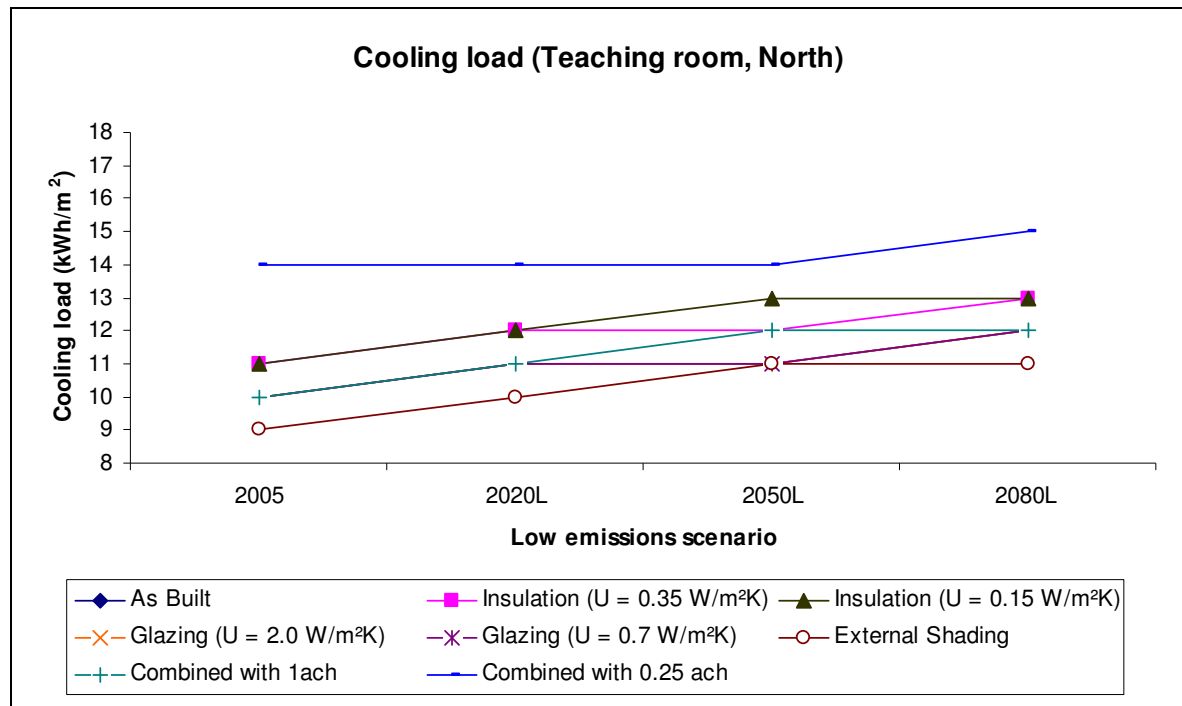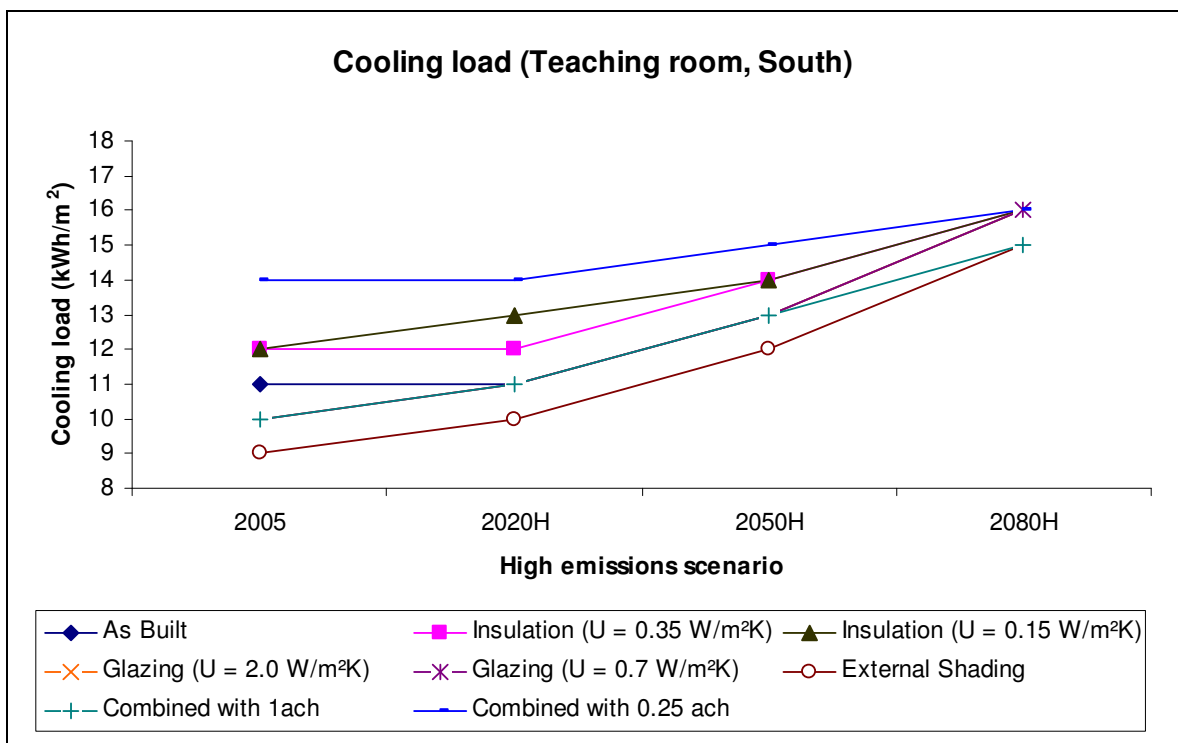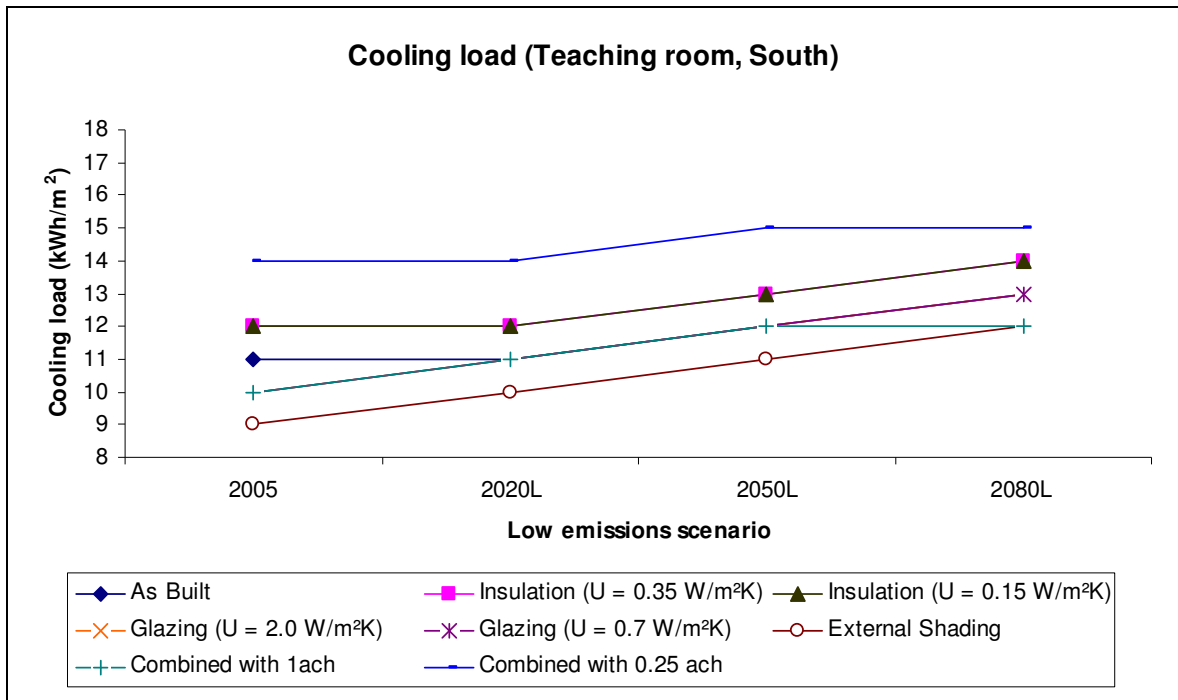
E1: Open-plan office

Total CO$_2$ (Open-plan office, South)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO$_2$ (Open-plan office, South)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO₂ (Open-plan office, East)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO₂ (Open-plan office, East)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO$_2$ (Open-plan office, West)

Low emissions scenario

- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO$_2$ (Open-plan office, West)

High emissions scenario

- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

E2: Teaching room

Total CO_2 (Teaching room, North) — Low emissions scenario

Total CO_2 (Teaching room, North) — High emissions scenario

Total CO$_2$ (Teaching room, South)

Low emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO$_2$ (Teaching room, South)

High emissions scenario

Legend:
- As Built
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Total CO$_2$ (Teaching room, East)

Low emissions scenario

Legend: As Built · Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Total CO$_2$ (Teaching room, East)

High emissions scenario

Legend: As Built · Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Appendix F: Saving in heating energy demand under different climate scenarios for different orientations of the open-plan office and the teaching room
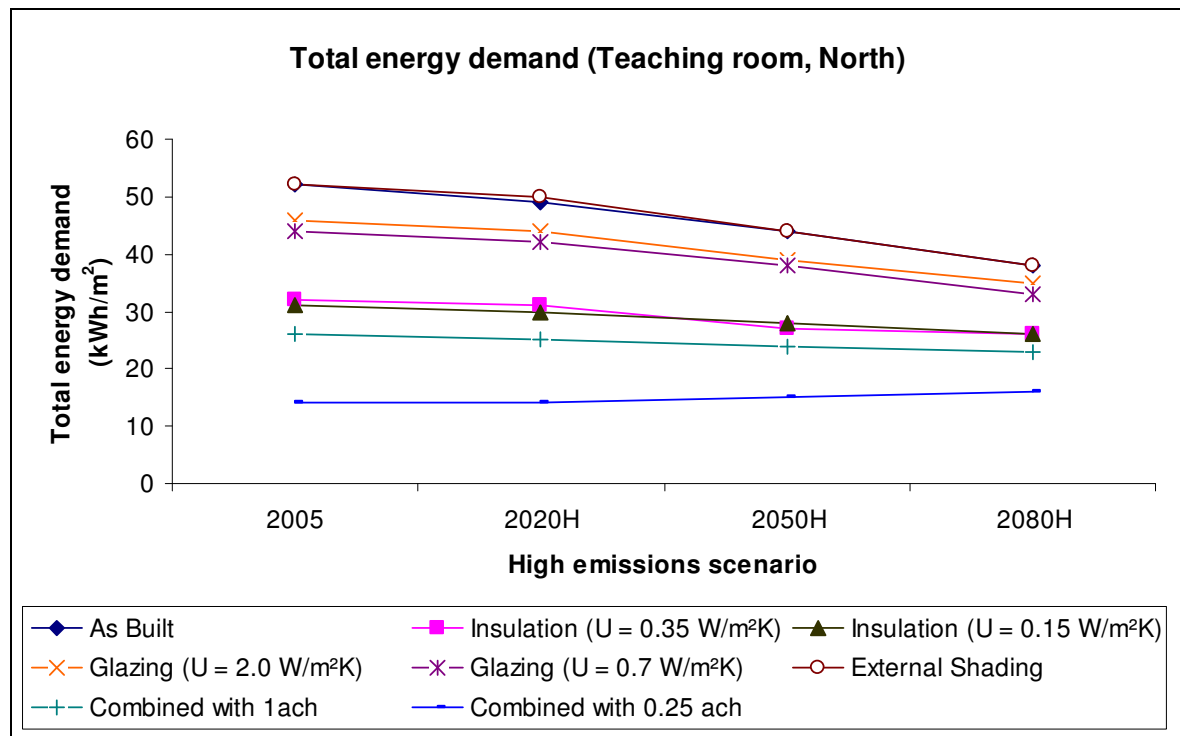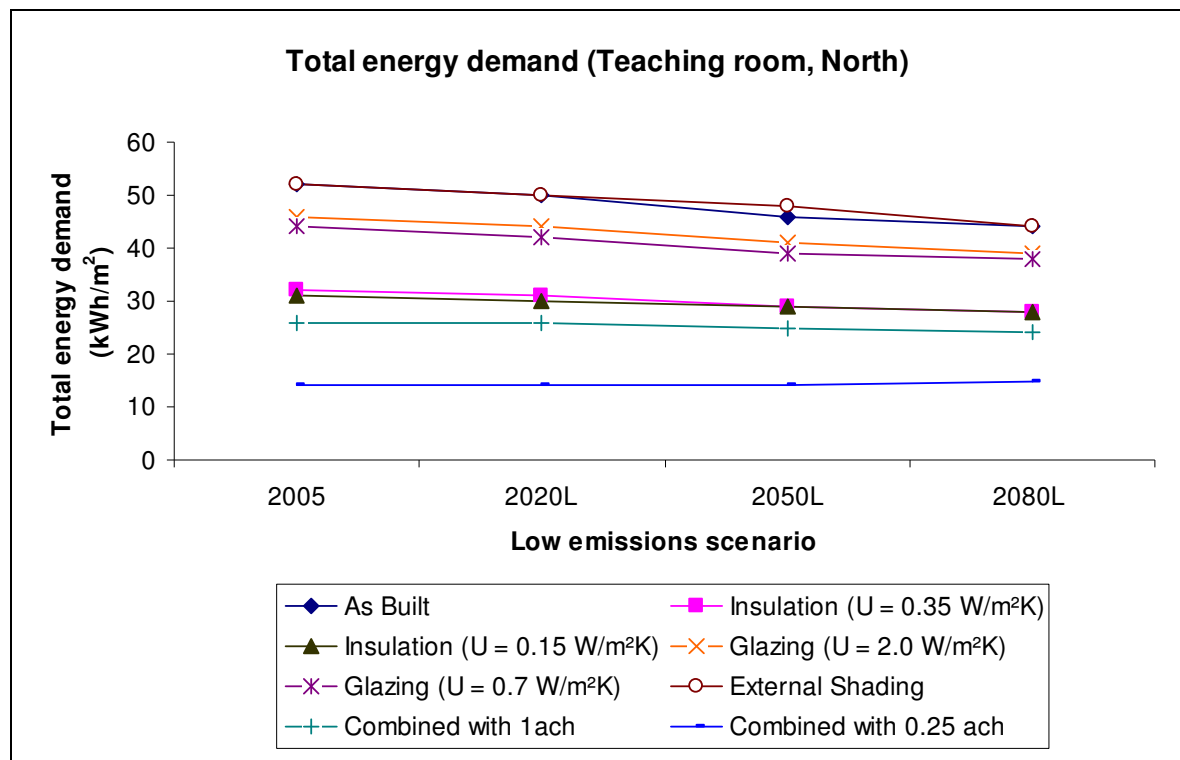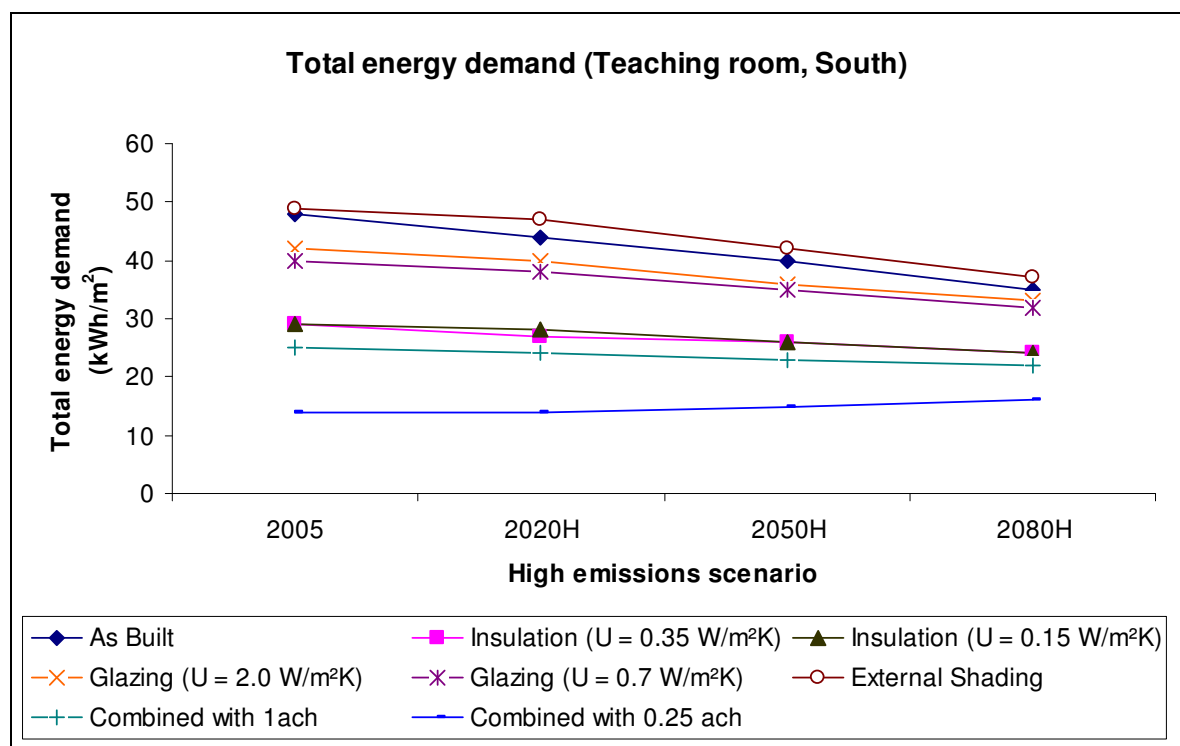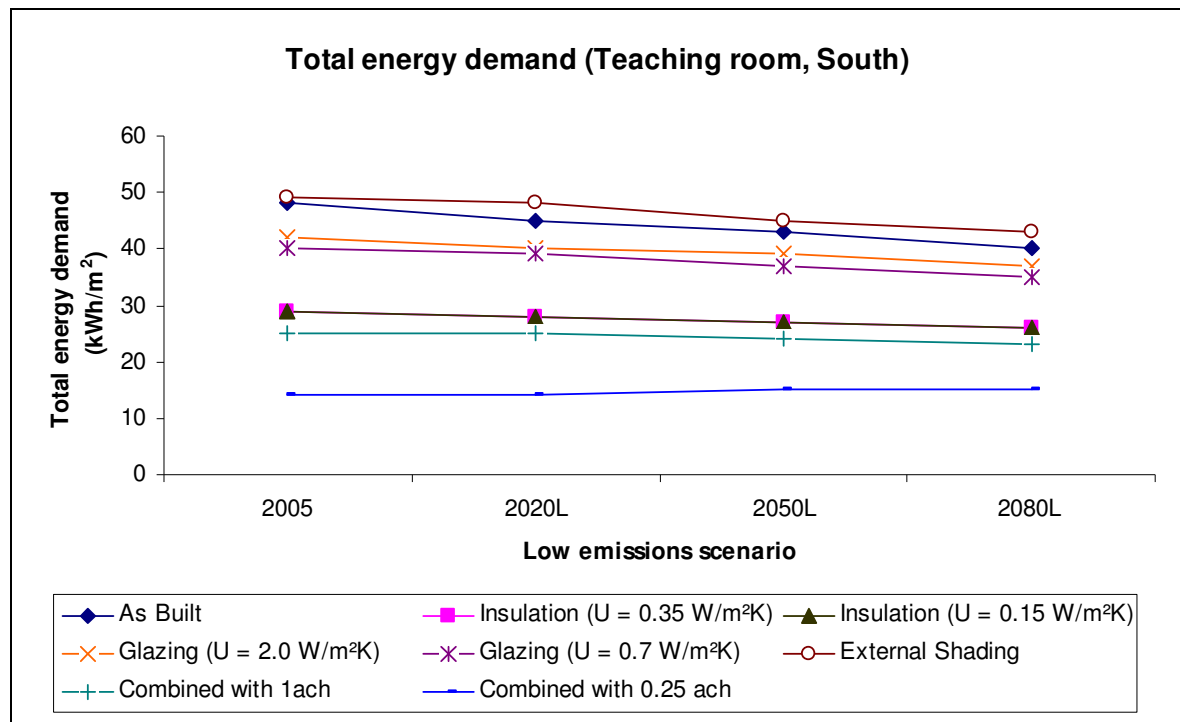
F1: Open-plan office

Saving in heating energy (Open-plan office, North)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Open-plan office, North)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Open-plan office, South)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Open-plan office, South)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Open-plan office, East)

Low emissions scenario

Legend:
- ■ Insulation (U = 0.35 W/m²K)
- ▲ Insulation (U = 0.15 W/m²K)
- ✕ Glazing (U = 2.0 W/m²K)
- ✳ Glazing (U = 0.7 W/m²K)
- ○ External Shading
- + Combined with 1ach
- — Combined with 0.25 ach

Saving in heating energy (Open-plan office, East)

High emissions scenario

Legend:
- ■ Insulation (U = 0.35 W/m²K)
- ▲ Insulation (U = 0.15 W/m²K)
- ✕ Glazing (U = 2.0 W/m²K)
- ✳ Glazing (U = 0.7 W/m²K)
- ○ External Shading
- + Combined with 1ach
- — Combined with 0.25 ach

Saving in heating energy (Open-plan office, West)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Open-plan office, West)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

F2: Teaching room

Saving in heating energy (Teaching room, North) — Low emissions scenario

Saving in heating energy (Teaching room, North) — High emissions scenario

Saving in heating energy (Teaching room, South)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Teaching room, South)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Teaching room, East)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Teaching room, East)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Teaching room, West)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Saving in heating energy (Teaching room, West)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Appendix G: Net saving in CO$_2$ emissions under different climate scenarios for different orientations of the open-plan office and the teaching room.
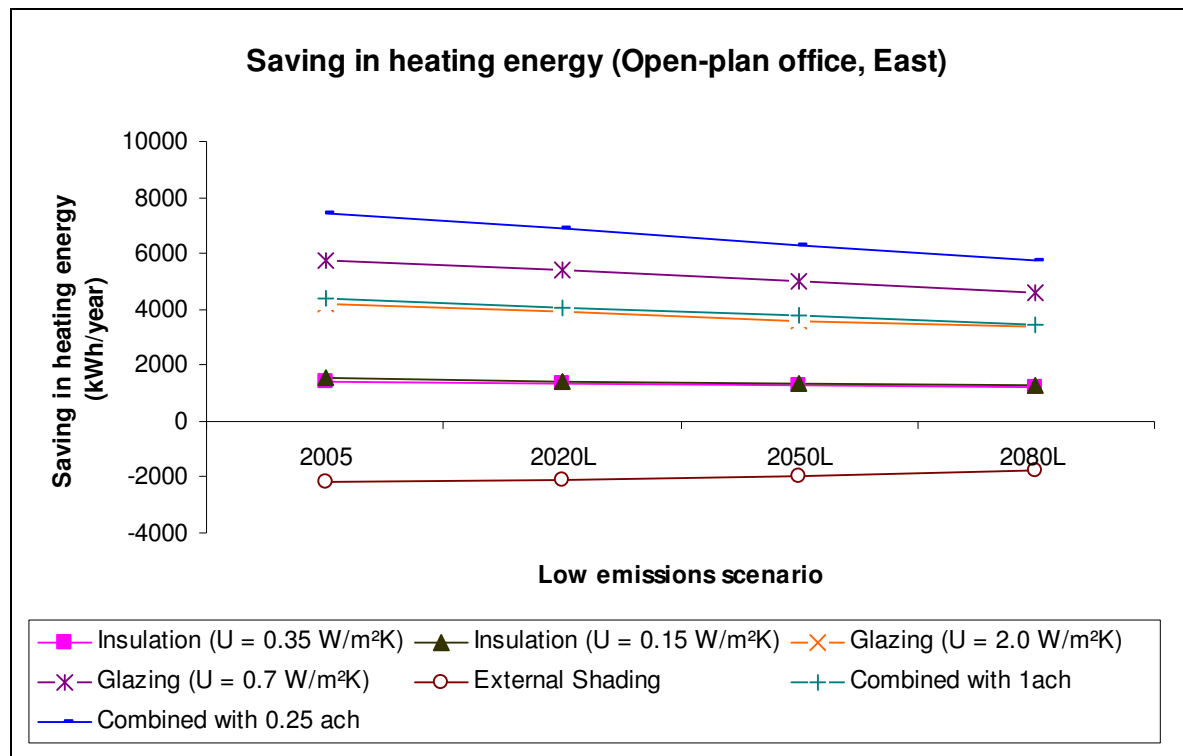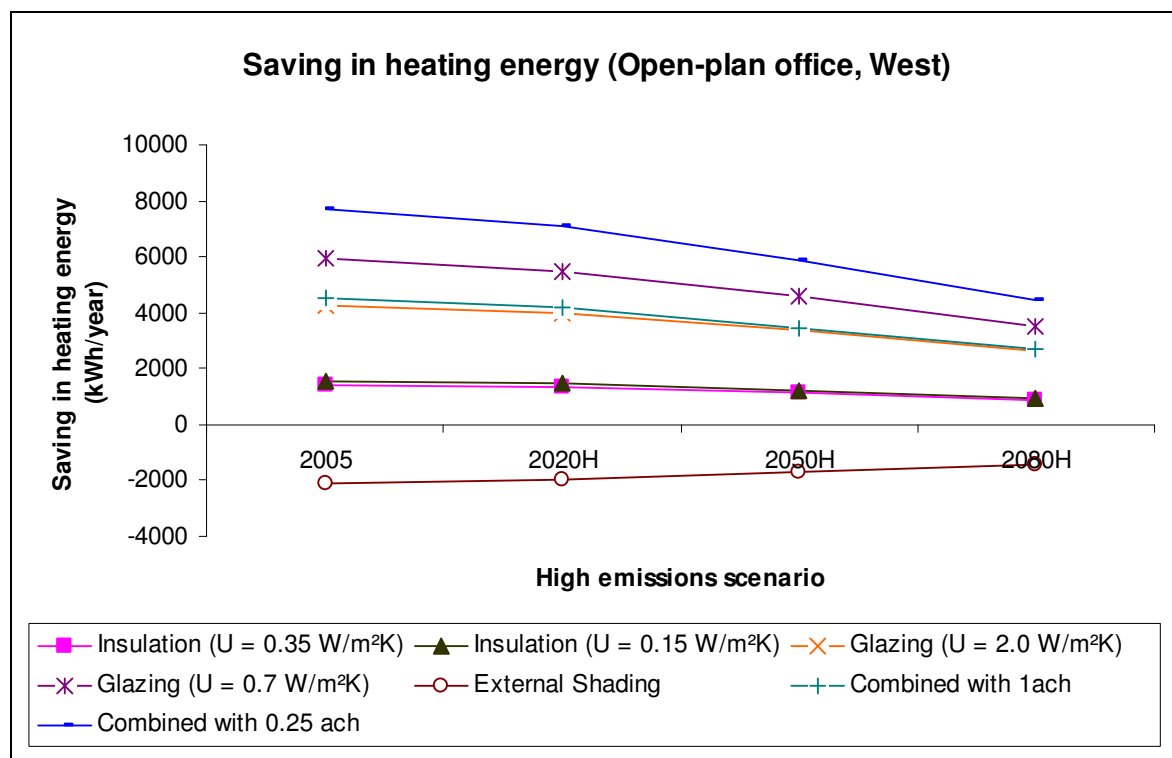
G1: Open-plan office

Net CO$_2$ savings (Open-plan office, North)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Open-plan office, North)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Open-plan office, South)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Open-plan office, South)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Open-plan office, East)

Low emissions scenario

Legend: Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Net CO$_2$ savings (Open-plan office, East)

High emissions scenario

Legend: Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Net CO$_2$ savings (Open-plan office, West)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Open-plan office, West)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

G2: Teaching room

Net CO$_2$ savings (Teaching room, North)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Teaching room, North)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Teaching room, South)

Low emissions scenario

- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Teaching room, South)

High emissions scenario

- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Teaching room, East)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Teaching room, East)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Teaching room, West)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net CO$_2$ savings (Teaching room, West)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Appendix H: Net saving in operational cost under different climate scenarios for different orientations of the open-plan office and the teaching room.
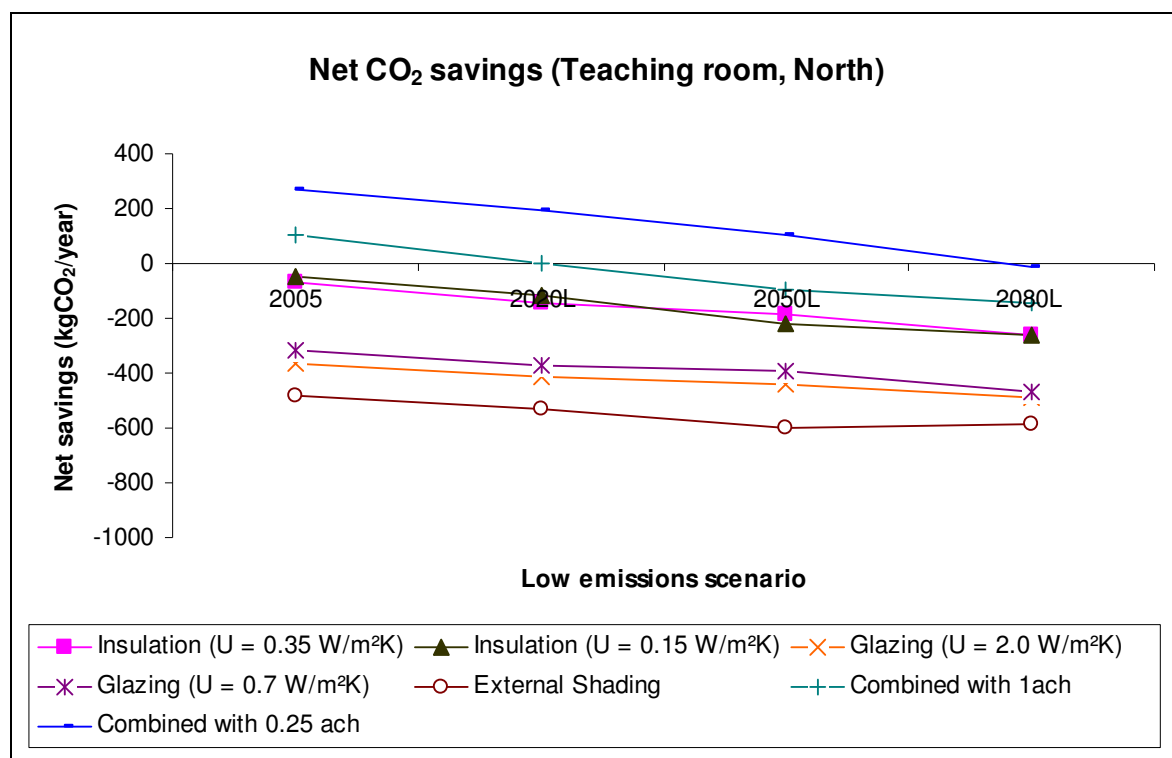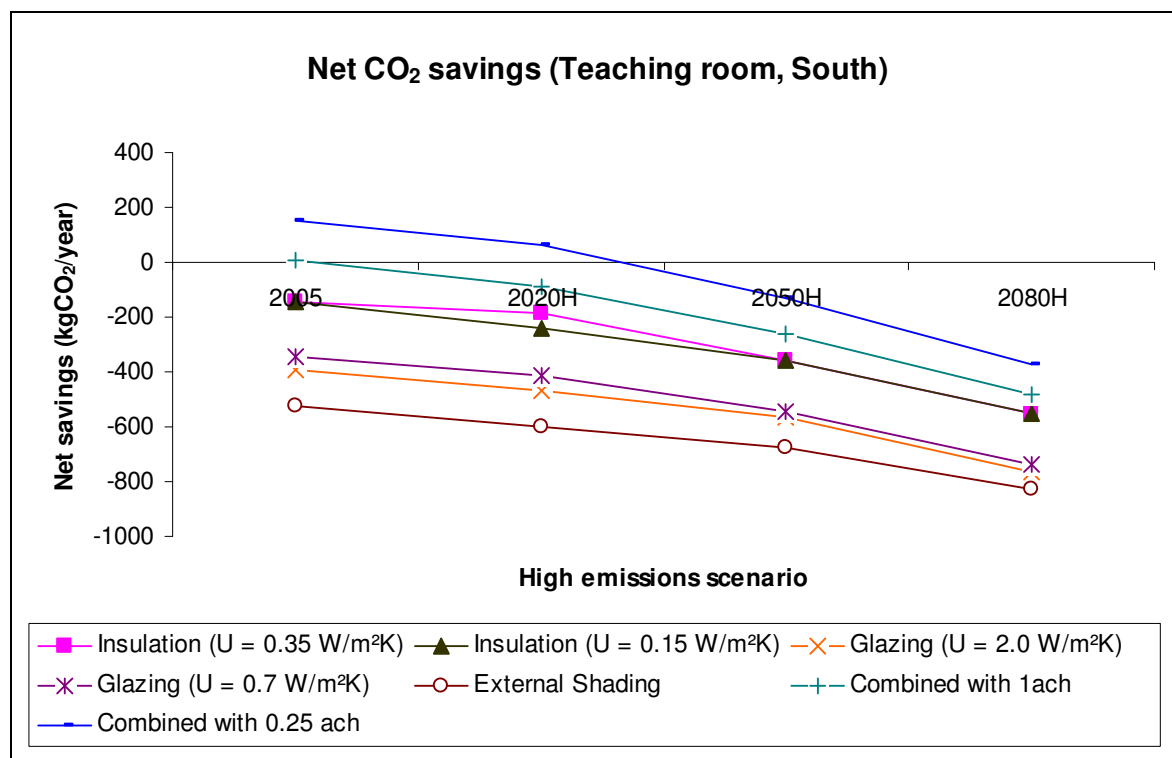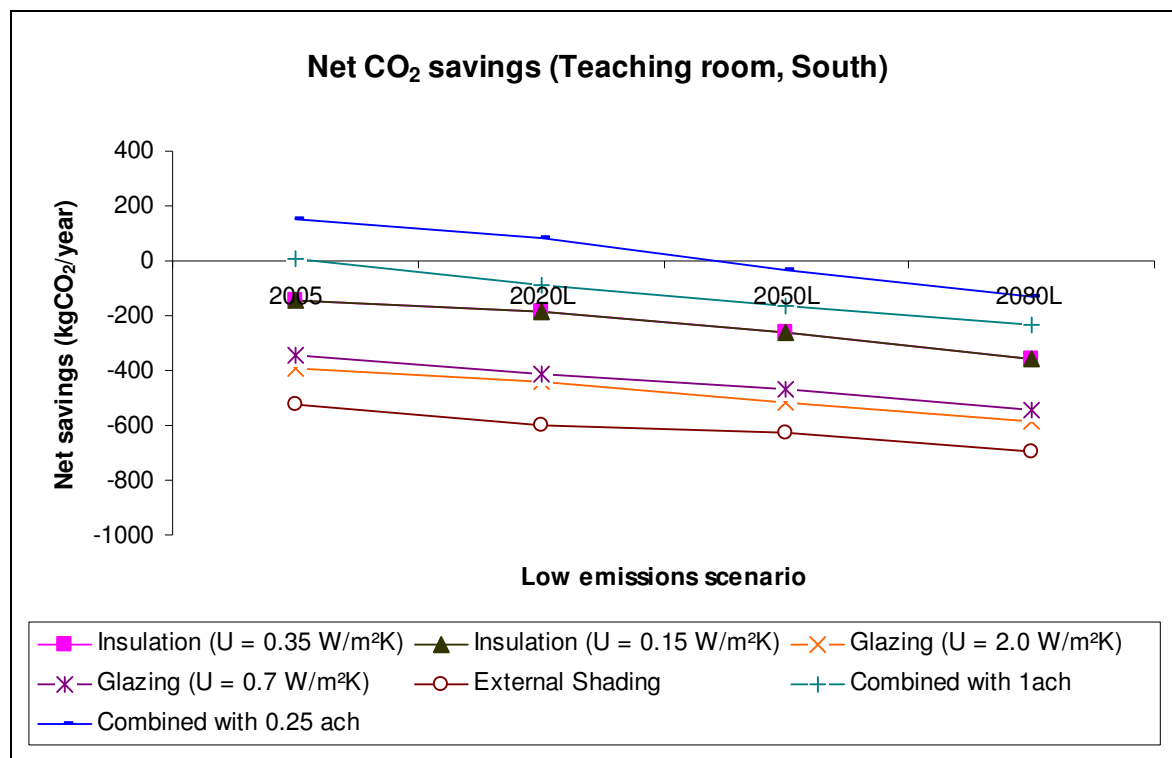
H1:Open-plan office

Net savings (Open-plan office, North)

Low emissions scenario

Legend: Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Net savings (Open-plan office, North)

High emissions scenario

Legend: Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Net savings (Open-plan office, South)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net savings (Open-plan office, South)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net savings (Open-plan office, East)

Low emissions scenario

Legend:
- ■ Insulation (U = 0.35 W/m²K)
- ▲ Insulation (U = 0.15 W/m²K)
- ✕ Glazing (U = 2.0 W/m²K)
- ✳ Glazing (U = 0.7 W/m²K)
- ○ External Shading
- + Combined with 1ach
- Combined with 0.25 ach

Net savings (Open-plan office, East)

High emissions scenario

Legend:
- ■ Insulation (U = 0.35 W/m²K)
- ▲ Insulation (U = 0.15 W/m²K)
- ✕ Glazing (U = 2.0 W/m²K)
- ✳ Glazing (U = 0.7 W/m²K)
- ○ External Shading
- + Combined with 1ach
- Combined with 0.25 ach

Net savings (Open-plan office, West)

Low emissions scenario

Net savings (Open-plan office, West)

High emissions scenario

H2: Teaching room

Net savings (Teaching room, North)

Low emissions scenario

Legend: Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Net savings (Teaching room, North)

High emissions scenario

Legend: Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Net savings (Teaching room, South)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net savings (Teaching room, South)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net savings (Teaching room, East)

Low emissions scenario

Legend: Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Net savings (Teaching room, East)

High emissions scenario

Legend: Insulation (U = 0.35 W/m²K), Insulation (U = 0.15 W/m²K), Glazing (U = 2.0 W/m²K), Glazing (U = 0.7 W/m²K), External Shading, Combined with 1ach, Combined with 0.25 ach

Net savings (Teaching room, West)

Low emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Net savings (Teaching room, West)

High emissions scenario

Legend:
- Insulation (U = 0.35 W/m²K)
- Insulation (U = 0.15 W/m²K)
- Glazing (U = 2.0 W/m²K)
- Glazing (U = 0.7 W/m²K)
- External Shading
- Combined with 1ach
- Combined with 0.25 ach

Appendix I: Net operational CO2 savings/embodied CO2 (OER) for different orientations of the open-plan office and the teaching room

I1: Open-plan office

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, North)

OER

Insulation (U = 0.35 W/m²K) · Insulation (U = 0.15 W/m²K) · Glazing (U = 2.0 W/m²K) · Glazing (U = 0.7 W/m²K) · External Shading · Combined with 1ach · Combined with 0.25 ach

Refurbishment option (No climate change)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, North)

OER

Refurbishment option (Low emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, North)

OER

Refurbishment option (High emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, South)

OER

Refurbishment option (No climate change)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, South)

OER

Refurbishment option (Low emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, South)

OER

Refurbishment option (High emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, East)

Refurbishment option (No climate change)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, East)

Refurbishment option (Low emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, East)

Refurbishment option (High emissions scenario)

**Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, West)**

Refurbishment option (No climate change)

**Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, West)**

Refurbishment option (Low emissions scenario)

**Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Open-plan office, West)**

Refurbishment option (High emissions scenario)

I2: Teaching room

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, North)

Refurbishment option (No climate change)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, North)

Refurbishment option (Low emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, North)

Refurbishment option (High emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, South)

Refurbishment option (Low emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, South)

Refurbishment option (No climate change)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, South)

Refurbishment option (High emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, East)

Refurbishment option (No climate change)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, East)

Refurbishment option (Low emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, East)

Refurbishment option (High emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, West)

Refurbishment option (No climate change)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, West)

Refurbishment option (Low emissions scenario)

Net operational CO$_2$ savings/embodied CO$_2$ (OER)
(Teaching room, West)

Refurbishment option (High emissions scenario)

Appendix J: Benefit cost ratio (BCR) for different orientations of the open-plan office and the teaching room

J1: Open-plan office

Benefit cost ratio (BCR)
(Open-plan office, South facade)

Refurbishment option (No climate change)

Benefit cost ratio (BCR)
(Open-plan office, South facade)

Refurbishment option (Low emissions scenario)

Benefit cost ratio (BCR)
(Open-plan office, South facade)

Refurbishment option (High emissions scenario)

Benefit cost ratio (BCR)
(Open-plan office, East facade)

Refurbishment option (No climate change)

Benefit cost ratio (BCR)
(Open-plan office, East facade)

Refurbishment option (Low emissions scenario)

Benefit cost ratio (BCR)
(Open-plan office, East facade)

Refurbishment option (High emissions scenario)

Benefit cost ratio (BCR)
(Open-plan office, West facade)

Refurbishment option (No climate change)

Benefit cost ratio (BCR)
(Open-plan office, West facade)

Refurbishment option (Low emissions scenario)

Benefit cost ratio (BCR)
(Open-plan office, West facade)

Refurbishment option (High emissions scenario)

J2: Teaching room

Benefit cost ratio (BCR)
(Teaching room, South)

Refurbishment option (No climate change)

Benefit cost ratio (BCR)
(Teaching room, South)

Refurbishment option (Low emissions scenario)

Benefit cost ratio (BCR)
(Teaching room, South)

Refurbishment option (High emissions scenario)

Benefit cost ratio (BCR)
(Teaching room, East)

Refurbishment option (No climate change)

Benefit cost ratio (BCR)
(Teaching room, East)

Refurbishment option (Low emissions scenario)

Benefit cost ratio (BCR)
(Teaching room, East)

Refurbishment option (High emissions scenario)

Benefit cost ratio (BCR)
(Teaching room, West)

Refurbishment option (No climate change)

Benefit cost ratio (BCR)
(Teaching room, West)

Refurbishment option (Low emissions scenario)

Benefit cost ratio (BCR)
(Teaching room, West)

Refurbishment option (High emissions scenario)