

MERITS OF USING LOW U AND G-VALUE FACADES ON HEATING/COOLING DEMAND AND CO₂ EMISSIONS FROM OFFICE BUILDINGS

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Doctor of Philosophy

DECLARATION

I, Wei Wang, confirm that the work presented in this thesis entitled 'Merits of using low U and g-value facades on heating/cooling demand and CO₂ emissions from office buildings' is my own. I confirm that:

- This work was done for a PhD research degree at University College London
- Where information has been derived from other sources, this has been indicated in the thesis

Signature:

Date: 9/6/2017

ABSTRACT

Office buildings are responsible for a significant amount of energy usage and CO₂ emissions, undesirable because of resource depletion and/or climate change. A possible strategy for reducing energy consumption and hence CO₂ emissions might be to specify high performance facades since they should reduce heat losses in cold conditions and conductive heat gains in hot conditions. This project reports on an investigation on energy demand and CO₂ emissions in office buildings incorporating facades with U-values between 1.2 to 2.6 W/m²K and g-values between 0.3 to 0.5, in four locations: London, Hong Kong, Caribou and Abu Dhabi which experience, respectively, cool, sub-tropical, cold and hot climates. Other variables considered include office orientation, long working hours, low internal gains and climate change. Energy demand was calculated using a steady-state method and the dynamic simulation tool, EDSL Tas. The results show that low U-value facades can reduce both annual energy demand and CO₂ emissions in locations with predominantly cold or predominantly hot environments such as those found in Caribou and Abu Dhabi. In Hong Kong U-value has a marginal effect on energy usage but savings can be achieved by specifying low g-value facades. In London, low U-value facades only decrease annual energy demand if internal gains are also low. However, reducing energy use does not necessarily reduce CO₂ emissions and if this is the goal a second strategy which emerges is to select facades which minimise energy demand when solar irradiations are low and maximising the use of, for example, solar energy and air/ground source heat pumps at other times. The work further suggests that Building Regulations should include a lower limit on U-value, a higher set point temperature in winter and more guidance on internal heat gains if energy use and CO₂ emissions are to be reduced in the UK.

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CHAPTER 1 INTRODUCTION

This chapter gives an overview of this research. It begins by introducing the background of the energy and environmental concerns of office buildings and summarises the key drivers for this research. This is followed by descriptions of the aims and objectives of this work. The outline of the methods used is then described. Lastly, the structure of the thesis is presented.

1.1 Background

Globally, great concerns exist over fossil fuel scarcity and greenhouse gas emissions which are believed to be causing global climate change. Global carbon emissions from fossil fuels have increased significantly since the beginning of the 20th Century: emissions increased by over 16 times between 1900 and 2008, and by about 1.5 times between 1990 and 2008. The rapid rise in CO₂ emission levels has persuaded countries to take measures to set targets for reducing their CO₂ emissions (UK Greenhouse Gas Statistics & Inventory Team et al. 2013).

For example, the UK is aiming to achieve an 80% reduction in its carbon emissions from 1990 levels by 2050, Department of Energy & Climate Change (DECC 2011). Likewise Hong Kong, along with other Asia-Pacific countries, is aiming to reduce carbon emissions by 25-65% of its energy consumption relative to 2005 levels by 2030 (Hong Kong Environment HKEB (2015). Hong Kong is a commercial city with limited industrial operations and buildings account for over half of total energy consumption (19% residential, 37% commercial).

Globally, buildings are estimated to be responsible for around a third of all CO₂ emissions (UK Green Building Council). Reducing carbon emissions from buildings is therefore essential for achieving global carbon reduction targets.

In the UK, buildings account for at least 45% of total carbon emissions (Oreszczyn et al. 2010). Most of the effort in this area to date has been focused on domestic buildings, but non-domestic buildings such as offices, which are also responsible for a large percentage of energy usage, have received less attention. This situation is only likely to get worse, given the UK government's decision to discard the zero carbon non-domestic buildings policy in 2019 as part of the zero-carbon Allowable Solutions, carbon offsetting scheme, announced in 2016.

Office buildings are an important type of non-domestic building and are an obvious sector to tackle, given that the energy consumed by these buildings is currently the second highest of the non-domestic building sector at around 17% (Pérez-Lombard et al. 2008). Moreover, in London, office buildings account for the highest percentage of the total non-domestic building floor space provision. According to Choudhary (2012), this is expected to increase by about 35% by 2050.

Given that around 54% of the total energy consumed in office buildings in the UK is required for heating and cooling (Pérez-Lombard et al. 2008), in Hong Kong space conditioning actually accounts for around 50% of energy consumption in office buildings (EMSD 2012). Therefore, it would seem reasonable to assume that the facade, being the barrier between the indoor and outdoor environment, has a crucial influence on total energy usage, and hence carbon emissions from these structures.

One possible way of reducing energy usage in office buildings in both London and Hong Kong might be to encourage the use of high performance insulation materials and glazing products that have been developed (Jelle 2011). Using these materials in curtain walls allows designers to provide thin and well-insulated facades with a high window-to-wall ratio. For example, vacuum insulation panels are able to achieve an overall U-value, which is calculated on the rate at which heat transfer through 1 m² of a structure, where the temperature difference between the inner and outer facade is 1°C, of 1.1 W/m²K with a window-to-wall ratio of 0.7. This is considerably better than the maximum recommended U-value for facades in the UK building regulations which is currently 2.2 W/m²K.

Fabric thermal efficiency is a function of the U-value: a lower U-value means better thermal insulation. In locations with a temperate climate such as the UK where external temperatures are generally lower than those indoors it is reasonable to assume that the provision of well insulated facades and roofs would reduce energy use. Low U-value facades should stop heat from escaping during cold weather conditions but also prevent heat from entering buildings during warmer periods. However, the studies that have been carried out on office buildings in both cold and hot climates appear to provide conflicting results.

For instance, the investigations of Pikas et al. (2014) involving a generic single floor of an office building in Estonia, where the climate is cold found that the most cost and energy efficient facade would be one with a low window-to-wall ratio, argon filled triple glazing and walls with 200 mm thick insulation, with a U-value of 0.16 W/m²K. Grynning et al. (2013) investigated the energy performance of windows in a Norwegian office by

varying both the U and g-values of the glass. The g-value, which indicates the proportion of the incoming solar energy converted into heat inside a building, is expressed as a number between 0 and 1, where lower values mean less solar heat transmission. The g-value generally accounts for the whole window including the effect of the frame. Grynning et al. (2013) found that despite the cold weather conditions, the cooling demand was high. But a study conducted by AECOM (2011) for UK conditions suggested that lowering the U-value from the currently recommended levels of 2.2 W/m²K for windows/curtains walls would have little benefit.

The benefits of increasing insulation levels in office buildings in warm/hot climates are equally unclear. McMullan (2007) states that specifying envelopes with high insulation levels should reduce energy usage since this reduces heat infiltration. This is confirmed in a study conducted by Aktacir et al. (2010) in Adana, Turkey, which has hot and humid summers and warm winters. These authors found that the best insulated walls decreased the design cooling load by up to 33%. However, Jong-Jin Kim et al. (2009) found that good envelope insulation did not provide much energy savings in hot climates. In Botswana where the climate is hot and dry, Masoso et al. (2008) found that at a certain combination of cooling-set temperature and internal gains there is a 'point of thermal inflection' where 'the higher the U-value the better'.

Furthermore, the energy usage of buildings is also related to other parameters such as building occupancy, orientation and ventilation. Thus, it is important to consider the influence of these parameters when assessing the energy performance of high performance facades.

Currently, there are two main uncertainties in office building design, and it is important to assess their effect on facade selection. The first is a significant 'performance gap', which is the difference found between the building's predicted and actual energy consumption, in the non-domestic building sector. The largest cause of the performance gap is inaccurate prediction of internal gains, which include over-usage of buildings and variations in internal heat gains. The second uncertainty is climate change. Both factors appear to have a great influence on the energy performance of buildings, therefore it is important to assess their effect on optimum facade design, aiming for 'future proof' buildings.

The fact that a performance gap exists means the current building regulations in the UK might not be sufficient to guide designers to use optimum facades that are resilient to both this factor and climate change.

1.2 Aims and Objectives

The aims of this research are:

- 1) To investigate the influence of low U and g-value facade on heating/cooling demand and CO₂ emissions in office buildings in four climatic zones, i.e. cold, cool, sub-tropical and hot.
- 2) To assess the impact of variations in working hours and internal heat gains, which are two aspects causing performance gap, on facade selection under the above-mentioned climatic conditions
- 3) To investigate the influence of climate change on facade selection under these four climatic conditions.
- 4) To investigate the influence of low U and g-value facades on CO₂ emissions of office buildings under these four climatic conditions.
- 5) Based on the results of these investigations, to elucidate the potential low U and g-value facades, to achieve the low carbon emissions goal in office buildings.
- 6) To assess the effectiveness of building regulations in the UK, and to propose appropriate improvements.

1.3 Research methodology outlines

To achieve the research aims and objectives above, the following research objectives are proposed:

- 1) A review of existing literature on the influence of facade design on energy demand and CO₂ emissions of office buildings under different climatic conditions. In addition, provide an overview of the current Building Regulation in the UK.
- 2) Building energy performance is a function of facade type and various other factors, for example built form, internal gains and climate. Therefore, this work will review the influence of each of these parameters on the energy performance of buildings, in order to highlight the relative importance of each on the facade type.
- 3) Select a method that is fit for purpose and develop a test programme that would assess the influence of climate, over-usage of buildings, lower internal gains and future climate change.
- 4) Use the developed method to investigate the influence of high-performance facades (low U and g-value facade) on office energy demand under assumed internal and external conditions.

- 5) Perform further calculations to investigate the influence of high-performance facades on office CO₂ emissions.
- 6) Further analyse the results and develop low-energy and low-carbon strategies in office building under different climatic conditions.
- 7) Further analyse the London results to make recommendations on possible improvements in the current building regulations, for reducing CO₂ emissions from office buildings.

1.4 Report overview

Chapter 2 introduces the challenges of designing low-energy and low-carbon offices globally. It then reviews the current developments of high-performance facades and existing studies related to the energy performance of high-performance facades. It also highlights the importance of assessing the variations in occupancy behaviour and climate change. These provide the rationale for the research questions summarised at the end of chapter.

Chapter 3 reviews past building energy simulation methods. It describes the proposed methods, which use steady-state calculations, alongside dynamic simulations carried out by Tas which is a building thermal analysis simulation software. Caribou (Maine, USA), London, Hong Kong and Abu Dhabi are selected to represent cold, cool, sub-tropical and hot locations. Climate data are included. A test programme is proposed at the end of the chapter.

Chapter 4 investigates the influence of high-performance facades on the energy required for heating and cooling office buildings in London under a number of operating conditions, including future changes in climate. The chapter presents the results from the steady-state calculation and the Tas simulation.

Chapter 5 investigates the influence of high-performance facades on the energy required for heating and cooling of office buildings in Hong Kong under a number of operating conditions, including future changes in climate. The chapter presents the results from the steady-state calculation and the Tas simulation.

Chapter 6 investigates the influence of high performance facades on the energy required for heating and cooling of office buildings in Caribou under a number of operating conditions, including future changes in climate. The chapter presents the results from the steady-state calculation and the Tas simulation.

Chapter 7 investigates the influence of high performance facades on the energy required for heating and cooling of office buildings in Abu Dhabi under a number of operating conditions, including future changes in climate. The chapter presents the results from the steady-state calculation and the Tas simulation.

Chapter 8 begins by summarising and further discussing the results in Chapters 4 to 7. This is followed by investigations of the influence of high-performance facades on the CO₂ emissions of office buildings in London, Hong Kong, Caribou and Abu Dhabi. Low-energy and low-carbon office design strategies are developed. Proposed changes to the UK's building regulations are also included at the end of the chapter.

Chapter 9 summaries the key conclusions, including the contribution of this thesis and proposals for possible future work.

CHAPTER 2 LITERATURE REVIEW

Introduction

Energy produced from fossil fuels might run out sooner than expected. Meanwhile, CO₂ produced by burning fossil fuels is a major component of greenhouse gases which is believed to be causing climate change and has caught global attention.

The building sector is energy intensive and produces a large amount of CO₂ emissions. Globally, buildings account for around a third of energy consumption and CO₂ emissions. Buildings have come to be perceived as the locus of energy use with the highest cost-effective energy saving potential. In the European Union (EU), buildings account for around 40% of the total energy demand and it is estimated that currently available energy efficient measures can save 28% of the total building energy demand cost-effectively (Ekins et al. 2008).

With a significant amount of work being put into reducing CO₂ emissions from domestic buildings, non-domestic buildings, especially high rise office buildings, is another sector to tackle. In office buildings, a large amount of energy consumption is associated with heating and cooling. The facade is a key element of office buildings which has great potential to reduce energy demand and hence CO₂ emissions.

The overall aim of this chapter is to review the literature on facades in order to identify a possible strategy for reducing energy demand and CO₂ emissions from office buildings. The chapter also reviews the literature on Building Regulations and how they have evolved in order to meet these needs. At the end of the chapter, research questions have been stated. We begin by discussing the global low carbon office building environment challenge.

2.1 Background: low carbon goals in office buildings

2.1.1 Global carbon reduction goals and non-domestic buildings

The atmosphere surrounding the earth behaves as a large 'greenhouse' around our planet and retains a certain proportion of heat received from the sun. Increasing certain greenhouse gases in the atmosphere leads to an extra amount of heat being absorbed and hence, reduces the amount of heat that the Earth would otherwise radiate back into space. This particular greenhouse effect causes additional heating of the planet, which is known as global warming (McMullan 2007). Figure 2.1 illustrates the major mechanisms of the greenhouse effect (NCCS 2017).

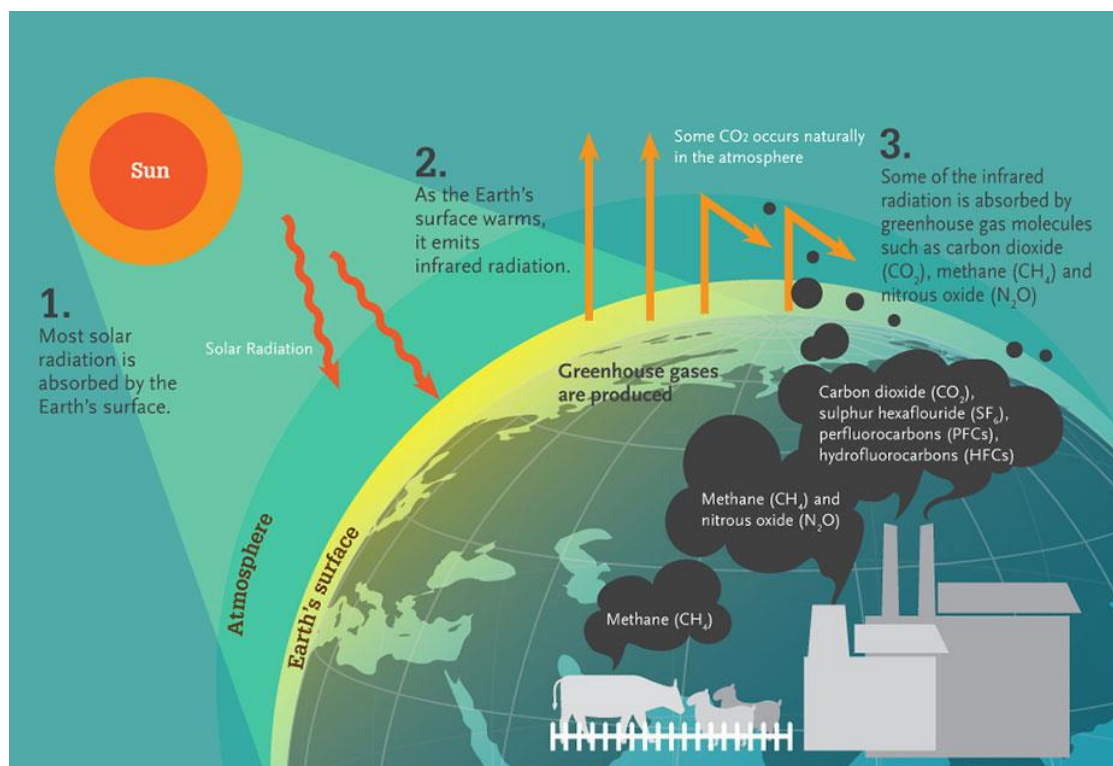


Figure 2.1 Mechanisms of the greenhouse effect (NCCS 2017)

From Figure 2.1 shows that production of the greenhouse effect includes four main mechanisms:

1. Electromagnetic radiation at most wavelengths from the sun passing through the Earth's atmosphere.
2. The Earth's surface absorbs electromagnetic radiation with short wavelengths and as a result, warms up. Then the heat is radiated from the Earth's surface back into space, as longer wavelength infrared radiation.
3. Some of this infrared radiation is absorbed by greenhouse gases in the atmosphere and is either re-emitted back to the atmosphere or out into space.
4. As a result of the above, the atmosphere warms up.

Greenhouse gases are gases that have a significant influence on the greenhouse effect, including water vapour, carbon dioxide, methane, nitrogen oxides, and chlorofluorocarbons. Greenhouse gases are produced from natural processes, for example, respiration by plants and animals generate carbon dioxide, and ocean evaporation produces water vapour (McMullan 2007). Human activities also increase the amount of greenhouse gases in the atmosphere, primarily by producing carbon dioxide through the burning of fossil fuels, which enhances the natural greenhouse effect. A certain amount of anthropogenic CO₂ is absorbed by our ecological system, which has natural sinks such as oceans and plants, which employ photosynthesis. However, the majority of anthropogenic CO₂ emissions cannot be removed by the natural system. It has been found that there is a rising amount of CO₂ emissions from ever more carbon intense economic activities, but a decline in the efficiency of natural CO₂ sinks on land and oceans. Consequently, the growth rate of atmospheric CO₂ emissions has increased rapidly since 2000 (Canadell et al. 2007).

A number of recent studies have identified a near linear relationship between global mean temperature change and cumulative CO₂ emissions (Friedlingstein et al. 2014). Prolonged periods of global warming causes climate change. The effects of climate change are shown by natural events such as warming oceans, sea level rise, shrinking ice sheets, glacial retreat, ocean acidification, and an increasing number of record high temperature events (NASA 2017). The global aim is to limit global warming by two degrees, by controlling the amount of CO₂ emissions (Meinshausen et al. 2009). However, this goal is only achievable if large and concerted global mitigation efforts are initiated imminently (Peters et al. 2012).

Anthropogenic CO₂ emissions arise mainly from burning fossil fuels, land use change, and industrial processes such as cement production (Olsen et al. 2006). The major consumers of fossil fuels are buildings and transport.

Carbon emissions from human activities are a great threat to the well-being of the planet and global effort is required to tackle this problem. Energy sources such as fossil fuels are also running out sooner than expected. Hence there is great incentive to reduce both energy usage and CO₂ emissions. Historically, there have been a number of carbon emission reduction treaties which demonstrate the global commitment to tackling these problems. For example, the Kyoto Protocol, an international treaty crafted by the United Nations Framework Convention on Climate Change (UNFCCC) in 1997, called for countries to commit to the reduction of greenhouse gases (GHG), including carbon dioxide (CO₂), or trade their emissions where necessary. The U.S.

target was a 7 percent reduction of 1990 levels by the year 2012. There are still ongoing efforts to reduce overall carbon emissions. The UK is aiming to reduce 80% of its Green House Gas (GHG) emissions, relative to 1990 levels, by 2050 (DCLG 2008). Similarly, various countries in the Asia Pacific region are aiming to reduce carbon emissions by reducing 25% of their energy consumption relative to 2005 levels by 2030 (Hong Kong Environment Bureau 2015).

Buildings are responsible for nearly one-third of the energy consumption and GHG emissions globally. Hence, buildings have been identified as a crucial area to reduce carbon emissions and alleviate energy consumption. There is a growing interest in the development of zero energy buildings in several countries (Li et al. 2013). Much of the work to-date has focused on residential buildings but non-residential buildings also have great potential to reduce carbon emissions. This is the case globally. There are plenty of statistics in the literature which show that non-residential buildings also have a big impact on energy use and CO₂ emissions.

For example, in the U.S., buildings account for 48% of total energy use and 73.1% of electricity consumption (Keeler et al. 2009). 40% of U.S. carbon dioxide emissions were from residential (22%) and commercial buildings (18%) in 2010 (C2ES 2012). Since 1990, the energy demand of commercial buildings in the US has grown at a rate of 2.9% per year and hence there is a pressing need to understand the energy performance of this type of building (Azar et al. 2012). In Europe, commercial and residential buildings together account for 39% of the total energy consumption within which commercial buildings take up 13% and residential buildings 26%. However, energy demand in non-residential buildings is expected to grow by 26% whereas for residential buildings this figure is around 12%. In the UK, a similar picture emerges. As shown in Figure 2.2, the non-domestic building stock was accountable for around 18% of total carbon emissions whereas domestic buildings contributed about 26% carbon emissions in 2003 (CarbonTrust 2008). However, 80% of the dwellings that we will be living in have already been built whereas by 2050, the total non-domestic floor area is expected to increase by 35%. Hence there is a significant energy saving potential for new non-domestic buildings.

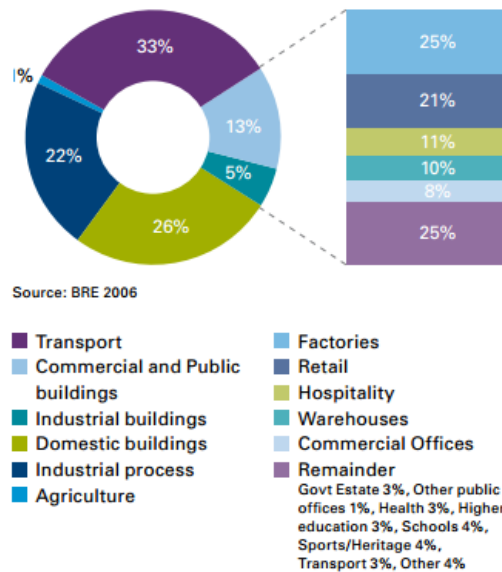


Figure 2.2 UK carbon emissions for the whole economy and broken down by non-domestic building type in 2003 (Carbon trust 2008)

2.1.2 Energy usage in office buildings

Office buildings are an important subset of non-residential buildings in terms of energy consumption intensity and built area. Non-residential buildings also include retail outlets, hotels, and restaurants. In the UK, office buildings are the second highest energy consumers in the non-domestic building sector (Table 2.1) and are responsible for around 8% of the UK's total carbon emissions (Figure 2.2). Office buildings consumption varies from 100 to 1000 kWh/m². In a developed city like London, offices account for the largest percentage of non-domestic space (Table 2.2).

UK	% Energy consumption
Retail	22
Offices	17
Hotels and Restaurants	16
Schools	10
Hospitals	6
Leisure	6
Others	23

Table 2.1 Energy use in non-domestic sector by building type (Pérez-Lombard et al. 2008)

Primary type	% Area
Office	30
Industrial	17
Retail	16
Education	14
Community	11
Hospitals	6
Hotels	2
Others	4

Table 2.2 Primary types of non-domestic buildings with percentage share of total non-domestic built area in london (Choudhary 2012)

Office buildings can be classified according to their size and mode of ventilation. Smaller scale offices tend to be converted from residential buildings and are naturally ventilated. Refurbished office buildings tend to have more conventional types of facades. The most energy intensive type of office buildings are newly built, prestige, air-conditioned environment with open plan offices which can vary from 4000 to 20,000m². This type of office building is normally a national or regional head quarter, or technical and administrative center (Energy 2003). A typical prestige air-conditioned office emits almost 4 times as much CO₂ per m² floor area as a typical naturally ventilated cellular office. The extra energy is used to deliver services such as heating, cooling, lighting and ventilation (Ramsay 2003).

Boyano et al. (2013) also found that in office buildings across Europe, the largest percent of energy consumption is associated with space heating, cooling and lighting. As shown in Figure 2.3, in air-conditioned office buildings, 54% for the total energy consumption is from heating, ventilation and air-conditioning (HVAC), followed 17% for lighting (Pérez-Lombard et al. 2008). It was also found that the CO₂ emissions from space conditioning accounts are high, around 50% in the UK offices (CIBSE 2012).

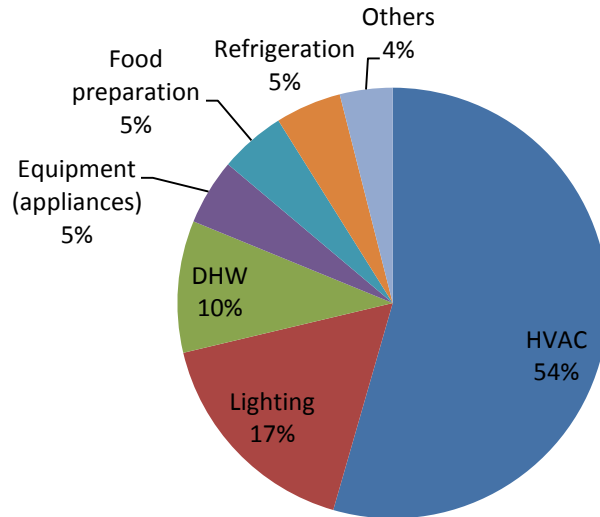


Figure 2.3 Energy consumption in air-conditioned offices by end use, UK(Pérez-Lombard et al. 2008)

Office buildings in China

The data on CO₂ emissions and energy use in office buildings in China exhibit similar trends. China agreed to cut CO₂ emissions intensity by 40%-45% below 2005 levels by 2020 at the United Nations Climate Change Conference in December 2009 (Wu et al. 2011). With continuing economic growth, the energy consumption of buildings is growing. Promoting energy efficiency and reducing the carbon emission rates of buildings is a top priority of the Chinese government, especially given the country's large population. The building sector accounts for about 25% of the total energy consumption in the country. More and more large commercial buildings with high window-to-wall ratios have been built over recent years. These large window systems cause energy concerns. In the northern part of China where the climate is cold, the heat dissipated from glazing systems accounts for about 40-50% of total heating load in winter while the cooling load caused by the glazing systems accounts for about 20-30% of the total cooling load in summer. The situation is found to be worse in the southern part of China (Yin et al. 2012).

Hong Kong is a commercial city with limited industrial operations and buildings (residential and commercial) account for over half the total energy consumption (Haase et al. 2009). Commercial buildings include restaurant, retail and accommodations and office buildings. It has been found that office buildings are responsible for 11% of commercial building energy consumption. Furthermore, in office buildings in Hong Kong, space conditioning accounts for around 55% of energy consumption (EMSD 2016).

2.1.3 Facade and building energy performance

Figure 2.4 shows the peak cooling load breakdown in an office building Hong Kong. It can be seen that around 35% of the peak cooling load is associated with conduction heat loss/gains through walls and windows and solar heat gain through windows. Zhuang; et al. (2014) assessed the energy saving potential of four energy efficiency measures for office buildings in Hong Kong, namely building envelope, building services, renewable energy and human behaviour. The analysis showed that because renewable energy requires further development and human behaviour is difficult to predict, building services and building envelope have the greatest potential to reduce energy consumption. Using more efficient HVAC systems and low-emissivity windows could reduce energy consumption in office building in hot and humid subtropical urban environments such as Hong Kong.

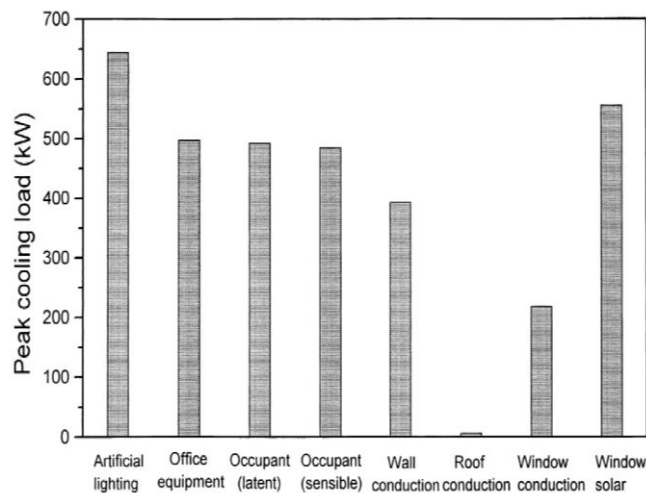


Figure 2.4 peak cooling load break down in an office in Hong Kong (Lam; et al. 1998)

Facade in the UK Building Regulations

Facades play an important role in the Building Regulations. For example, Part L of Schedule 1 of the UK's Building Regulation 2010 includes two provisions for conservation of fuel and power:

- I. limiting heat gains and losses through thermal elements and other parts of the building fabric; and from pipes, ducts and vessels used for space heating, space cooling and hot water services
- II. providing energy efficient building services

It can be seen in the building regulation that there are two main approaches to reduce energy usage in buildings. While one addresses designing energy efficient building

services, improving facades' U-value has been identified as an important measure in the Building Regulations to save buildings' energy usage. Similar measures are found in the Building Regulations all over the world, for example, the European Commission states different limits for U-values according to climates in 'Implementation of the Energy Performance of Building Directive, Country reports, 2008 (DGET 2008).

Facade and building life cycle energy performance

The past literature has also recognized that the facade is an important building element which affects buildings' energy consumption and CO₂ emissions. A few authors used life cycle assessment framework to evaluate and compare the impact of facade systems on buildings' energy consumption and CO₂ emissions.

Life cycle assessment involves quantifying and evaluating the material and energy flows of a system. It is generally recognized that there are six phases in a building's life cycle: raw material extraction and components production, transport, construction, operation, maintenance, and demolition. Life energy consumption of a building includes its embodied energy and operating energy. Embodied energy is defined as the energy used during material extraction and production, replacement and demolition phase whereas operating energy is 'the energy required to operate the building in processes, such as space conditioning, lighting and operating other building appliances, (Dixit et al. 2012).

Current research has shown that the operating stage of the building contributes the largest amount of CO₂ emission. In conventional buildings, operating energy can be as high as 80-90% of total life cycle energy consumption followed by embodied energy which is around 10-20%.(Ramesh et al. 2010). However, with the development of low energy buildings where operating energy is being kept at the minimum, the embodied energy has become more significant. For example, Radhi (2009) studied the direct (embodied energy) and indirect (building's operating energy) impact of five types of cladding materials used in barrier wall systems on the CO₂ emissions of an educational building in United Arab Emirate. Cladding materials studied are stucco, masonry veneer, aluminium siding, vinyl siding and the exterior insulation and finish systems (EIFS). The environmental performance, economic and energy performance of these five types of walls are analyzed. Results indicated that each wall type has its own potential in CO₂ reductions in both the manufacturing stage and building's operating stage. The selection of facade should not only be based on the aesthetics and cost, which is often the case, but also its environmental and energy performance.

It can be concluded that energy consumption and CO₂ emissions associated with heating and cooling of office buildings are significant globally, especially in major cities like London and Hong Kong. It would seem reasonable to assume that the facade being the barrier between the indoor and outdoor environment has a crucial influence on total energy usage and hence carbon emissions from these structures. The next section briefly looks at how facades influence heat/cooling load in buildings.

2.1.4 Facade and heating/cooling load calculation

The thermal properties and the design of facades have important roles in determining the heating and cooling energy demand of buildings. This section briefly introduces the physical principles of the energy demand calculation in order to demonstrate the relationship between facades' properties and the energy demand of office buildings.

Heat balance principle

Heat is a form of energy and it is normally measured in joules (J). When it is added to a substance, it causes the substance to rise in temperature, fuse, evaporate, or expand. Heat always flows from a hotter area to a colder area. The widely used measurement of heat in SI units is kilowatt hour (kWh).

Heating and cooling loads are the thermal energy that must be supplied or removed from the interior of a building in order to maintain the desired comfort conditions. This is the demand side of the building. Heat balance sums up the heat transfer into and out of a building space and is the fundamental principle in all energy prediction tools. In the calculation process, one needs to provide a careful account of all these thermal energy terms in a building. The total energy must be conserved according to the First Law of Thermodynamics which states that 'the energy flowing into a control volume is equal to the energy flowing out of a control volume less the energy stored within the control volume'. It can be expressed as:

$$\text{Energy in} = \text{Energy out} - \text{Energy stored}$$

Equation 1

Figure 2.5 illustrate the major aspects that affect the heat transfer of buildings, they are the external climatic condition, internal conditions and building fabric properties. Principal influencing aspects of the external climatic condition includes dry bulb air temperature, direct and diffuse solar radiation, relative humidity, wind speed. For heating and cooling load calculation, temperature and solar radiation on vertical surfaces are more often used. Internal conditions include the indoor design

temperature, required humidity and internal heat gains from lighting, equipment and occupants.

The building fabric properties determine the rate of heat transfer into and out of buildings. It includes facade's U-value and solar gain factor, which is g-value. U-value, sometimes referred as thermal transmittance, is a measure of heat loss through a structural element. It is calculated on the rate at which heat transfers through 1 square meter of a structure, where the temperature different between the inner and outer facade is 1 degree Celsius. Its unit is W/m^2K . The g-value, which indicates the proportion of the incoming solar energy converted into heat inside a building, is expressed as a number between 0 and 1, where lower values mean less solar heat transmission.

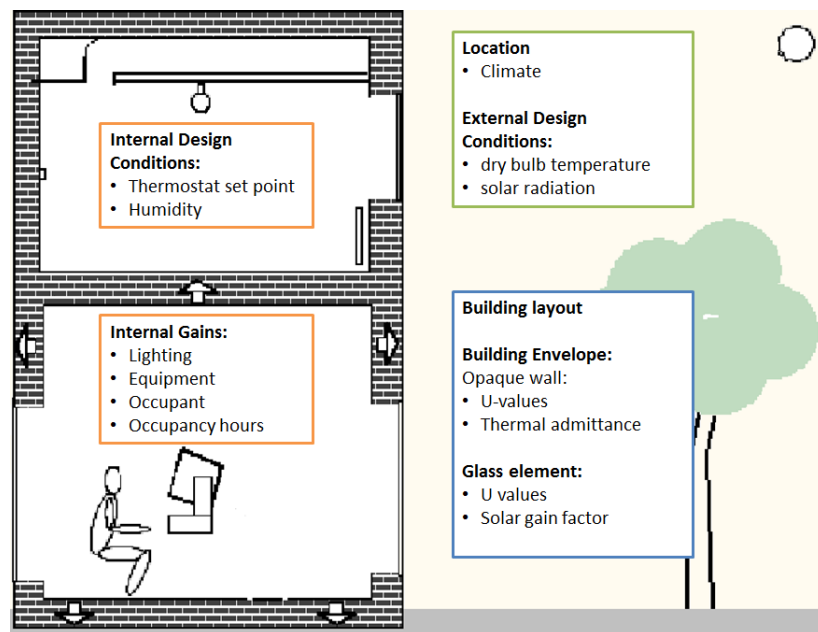


Figure 2.5 An illustration of building parameters affecting thermal performance of buildings (adapted from Tas Theory Manual)

Table 2.3 summarises some of the major heat transfer mechanisms happen in a building.

Building envelope elements	Transfer mechanisms
Opaque walls	<ul style="list-style-type: none"> Conduction heat gain/loss
Windows (glass)	<ul style="list-style-type: none"> Conduction heat gain/loss Solar radiation heat gain
Ground	<ul style="list-style-type: none"> Conduction heat loss
Internal elements	Transfer mechanisms
Lighting, equipment, occupants	<ul style="list-style-type: none"> Convection and radiation
Air conditioning	<ul style="list-style-type: none"> Convection

Table 2.3 Summary of heat transfer mechanisms in building environment

Calculating the energy demand

The heat balance equation is used to calculate the extra energy needed to balance the losses and the gains and to give a constant temperature. It consists of the heat coming in/going out of a building space. The inside temperature of a building is kept constant and this generally requires heating or cooling.

Energy for heating or cooling=

fabric heat loss + ventilation heat loss - solar heat gains - internal heat gains

Equation 2

1) Fabric heat loss is caused by the transmission of heat through the materials of walls, roofs and floors. Assuming steady state conditions, the heat loss for each element can be calculated by the following formula,

$$Q_{\text{cond}} = UA\Delta T$$

Equation 3

Where,

Q_{cond} = rate of fabric heat loss = heat energy lost/time (W)

U = U-value of the element considered ($\text{W}/\text{m}^2\text{K}$)

A = area of that element (m^2)

ΔT = Difference between the temperatures assumed for the inside and outside

2) Ventilation heat loss from a building is caused by the loss of warm air and its replacement by air that is colder and has to be heated. Therefore, it depends on the temperature difference between the indoors and outdoors as well as the rate of the air exchange.

3) Solar heat gains are the heat that buildings get from the sun. Solar radiation from the Sun is either reflected back to space or is diffused and absorbed by the earth's atmosphere. The intensity of solar radiation falling on a surface depends on its location, orientations, the clearness of the atmosphere, and the time of year (Mull 1995). Solar heat gains in buildings can occur in two ways – conduction through the opaque walls and glazing, and radiation through the glazing. Among these, radiation through the glazing has the highest impact on internal building temperatures.

4) Internal heat gains are the heat given off by various activities and by equipment in a building that is not primarily designed to give heat. The major sources of such heat are heat from people, lighting and equipment.

Therefore, at a given location for given internal conditions, it will be appreciated that the thermal performance of buildings is largely determined by the facade system. This is because both fabric heat loss and solar heat gains in the heat balance equation depend on the properties of the facades. The construction of the facade can be represented by its U-value and g-value. More details of the relevant parameters are introduced in the later part of this chapter, and the full expression of the equation is included in Chapter 3.

The great environment problem and current building legislation both drive the construction industry to design more energy efficient and environmental friendly office buildings. Both research and building regulations have identified the important role of the facade in thermal performance of non-domestic buildings. Fabric thermal efficiency is a function of the U-value: a lower U-value means better thermal insulation. Low U-value facades should stop heat from escaping during cold weather conditions but also prevent heat from entering buildings during warmer periods. The next section introduces the curtain wall system and then explores recent developments in curtain wall system design in light of the more stringent building energy code and the on-going carbon reduction targets.

2.2 High performance facades in office buildings

Facade being the barrier between indoor and outdoor has changed its form over the years. The most common wall type used in high rise office buildings is a curtain wall which is a type of non-load bearing wall. High performance facades in office buildings use advanced insulation materials and technologies to achieve superior thermal performance while being very thin. This section reviews the historical development of curtain walls and the state of art technologies used to improve the energy performance of them.

2.2.1 Historical development of walls

Buildings fulfil the need of humans to have a safe and comfortable environment. The fundamental function of buildings is to protect occupants from external weather, for example wind, sun and rain. Originally, buildings had simple forms (Figure 2.6 A) using materials such as reeds and mud which were usually locally available. As society flourished, brick became available and for several thousand years, walls in Europe and elsewhere were built of masonry, wood or clay (Figure 2.6 B). Masonry walls are massive, strong and durable and have the advantages of natural heat storage and good thermal insulation.

After the Industrial Revolution, new materials and techniques emerged. Materials such as steel, concrete and glass became more commonly used in the construction industry. Also, building enclosures began to be separated from the main building structure. The mainstream wall system for offices changed from load-bearing to non-load bearing. Buildings with non-load bearing curtain (Figure 2.6 C) walls are usually referred to as lightweight buildings. Lightweight buildings have four main separate components (Brock 2005):

- The form-giving structure
- The equipment and systems that help control the interior environment
- The partitions and finishes defining the interior function
- The building envelope (the exterior wall, the roof, openings within the envelope, and the foundations)



A)

B)

C)

Figure 2.6 Evolving built forms

Light-weight buildings have many advantages that architects and clients desire. They enable designers to build taller buildings and employ faster construction processes. They also allow large expanse of glazing area which allow more natural lighting and increase buildings' aesthetic value.

The increased use of light-weight buildings has coincided with an increase in environmental awareness. Taller buildings mean structures are exposed to greater environmental extremes. High usage of glass causes glare and rapid temperature fluctuations. The control of the interior environment, the flow of heat, air, noise and water vapour has also become more complex. The durability of thinner walls is also a problem. Hence more mechanical conditioning is required which leads to greater use of electricity. Thus, a conflict has arisen between structural lightness and environmental efficiency (Cowan 1977).

A building's 'envelope' is the interface between the interior and exterior environments of the building. In large buildings, windows and metal and glass curtain walls generally represent as much as 50-100% of the exterior cladding, and are therefore considered determining elements in the performance of the vertical building envelope. They are an important architectural feature of a building and represent a significant portion of the overall cost of a building's construction, or of a renovation project (Goncalves et al. 2010).

Over time, building envelopes have been used to perform various functions. These include the control of physical environmental factors that provide comfortable temperatures and natural lighting, acoustic separation, resistance to rain and moisture penetration, as well as air leakage and wind load. Structurally, the façade transfers lateral loads from wind and seismic events to the building structure; additionally, the

building also has to support self-weight. Accommodation must also be made for movement between the different components within an assembly, and for between the assemblies of the exterior wall and the structure. Other important design aspects are fire safety, security, energy conservation, and aesthetics (Brock 2005).

The basic requirements of a building's envelope for responding to diverse functional and climatic demands have remained the same since medieval times. However, expectations have vastly increased over time in terms of both absolute performance, and facades' ability to provide the desired level of control over the external environment. Based on a society's composition and economic conditions, and the needs and functions of the exterior envelope, decisions may vary considerably. In addition, the extensive use of highly-glazed building façades has created a challenging dilemma for the design and manufacturing community. Table 2.4 lists some of the modern façade design solutions that protect the indoor environment from the outdoor climate, as summarised by Kazmierczak (2010).

Rain	Waterproofing, seals, and screens
Sun	Shading and window coatings
Heat flow	Thermal insulation, low emissivity, and absorptivity surfacing
Wind, blast	Controlled by a continuous path of structural resistance
Water vapour	Vapour retardant and permeable layers
Noise and vibrations	Addition of mass, damping, and skewing
Fire	Thermal resistant layers

Table 2.4 Façade' elements and their functions

Façade and building's performance

A number of aspects pertaining to a building's performance is summarised by Preiser et al. (2005) as follows.

1. Health, safety, and security performance
2. Functionality, efficiency, and workflow performance
3. Psychological, social, cultural, and aesthetic performance

In other words, as described by Leaman et al. (2010), building performance depends on how well occupants' needs are met, as well as the building's environmental performance, which primarily includes energy and water efficiency. Additionally, Leaman et al. (2010) point out another important aspect of building performance, which is whether buildings are economic; this includes aspects such as value for money and return on investment.

A façade's thermal properties affect a building's operating energy and embodied energy and hence, its environmental performance. Durability and maintenance affect building costs. Facade design affects a building's lighting level and thermal comfort. Constructing a façade affects the entire building in terms of manufacturing costs and constructability. The physical comfort of humans greatly depends on temperature, quality of air, lighting environment, and acoustic environment. Heat energy and other thermal properties are major factors in maintaining human bodily comfort and therefore also play important roles in the performance of buildings.

Considering all of the above aspects, this project focuses on the influence of façade on energy and the environmental performance of buildings. The transfer of thermal energy through the fabric of buildings is the dominant factor for creating an energy balance within buildings. Thermal insulation is a major factor for reducing heat loss from buildings; therefore, adequate insulation should be a feature of good initial design. The relatively small cost of extra insulation materials can be quickly paid for by a reduction in the size of the heating plant required, and by annual savings in the amount of fuel needed. These fuel savings, and the related reductions of carbon emissions, continue throughout the life of the building.

Apart from the façade, building fabric also includes materials for a roof. Heat exchange takes place through both the roof and the ground. However, for high- rise offices, the

façade is where the majority of heat exchange occurs. The rest of this section mainly reviews the current technologies enhancing façades thermal performance.

2.2.2 Introducing curtain walls

Curtain walls are non-load bearing walls which are the most commonly used facade system used in newly built high rise office developments which are the most energy intensive office type. The facade is an important element especially in high rise office buildings where its wall to building volume ratio is higher compared to other building forms.

Figure 2.7 shows a typical curtain wall construction. It can be seen that curtain walls can be separated into framing and panels. Panels are composed by a glass/vision area and a spandrel/non-vision area. The spandrel areas are often multi-layered with insulations inserted in the middle. The outer layers of the spandrel can be made by a range of materials such as glass, metals or stone veneer. Vision glass may be double or triple glazed. Curtain wall frame is commonly made by aluminium.

The design of frame and panels are very complex because curtain walls need to fulfil a number of functions. They have to provide thermal insulation and at the same time fulfil other functional needs such as transferring load back to the primary structure of the building, providing fire and acoustic separations, etc..

There are a few different curtain wall systems which the components are assembled: stick system, unitized system. Stick systems are installed piece by piece on site, with the glazing inserted into the frame from the inside or the outside depending on access conditions. Unitised systems are pre-fabricated in modules off-site and delivered in panels. Unitised systems are better able to exploit the benefits of factory condition manufacturing and quality control and require lower installation time on site. Figure 2.7 shows a stick system curtain wall.

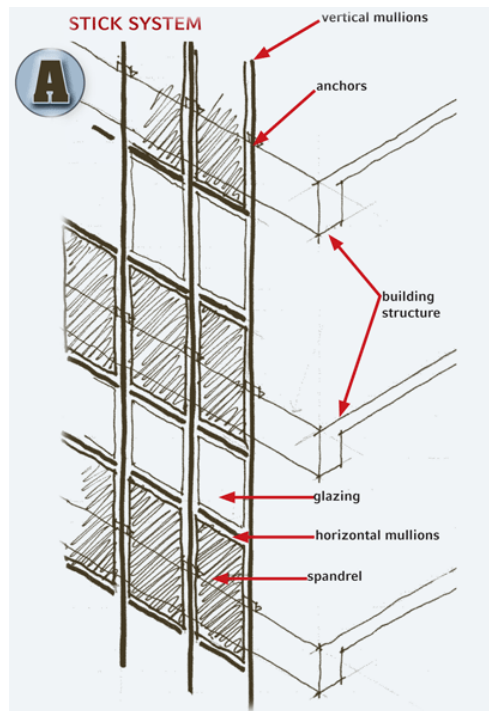


Figure 2.7 curtain wall scheme diagram (Pilkington)

a) Curtain wall thermal properties

Curtain walls affect the energy demand of buildings via two properties: its insulation level represented by U-value, and its g-value which determines the amount of solar heat transmission. The lower the overall U-value of the building envelope, which is the overall U-value of opaque walls, windows and frames, the better the insulation which means there is less heat transfer across the envelope. Adequate insulation level can reduce the heat loss to the environment and hence reduce heating demand in cool climates. It can also reduce the heat infiltration where the climate is hot, reducing the cooling needs. The second property is its g-value which determines the proportion of the solar heat gain from the Sun transmitted through the glass panel to the indoor environment.

Another important property of walls is thermal mass. Thermal mass of a building can be represented by the thermal admittance (Y-value) and determines its response to variations in temperature. Typically, the value is $19\text{W/m}^2\text{K}$ for a heavyweight building constructed with a solid floor and masonry walls with dense plaster whereas around $5\text{W/m}^2\text{K}$ for a lightweight building, which is typically constructed with a suspended timber floor, and framed walls with plasterboard (McMullan 2007). Figure 2.8 further illustrates the difference between lightweight structure and heavy weight structure. The effect of thermal mass for lightweight curtain wall is small and hence is not discussed in this work

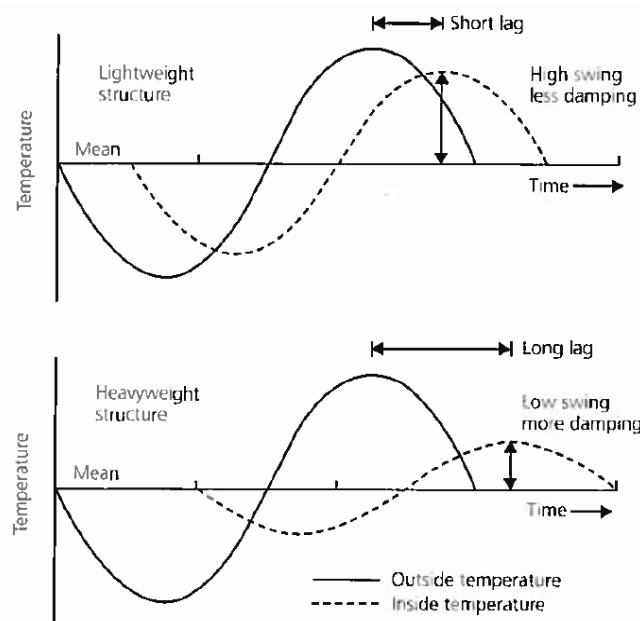


Figure 2.8 Thermal response of lightweight and heavyweight building structure (McMullan 2007)

b) High performance facade development

As office buildings have become taller, facade manufacturers have developed thinner and better insulated walls, especially there are more stringent energy requirements set out in Building Regulations and codes, for example, the European Performance of Buildings Directive (EPBD). In the market, a range of high-performance facade products using advanced materials have been developed to use in curtain walls with the aim of meeting the near-zero-energy and low carbon building challenges.

Curtain walling is classed as glazing in the building regulations; the current maximum allowable U-value for curtain walling is $2.2 \text{ W/m}^2\text{K}$ in the UK's Building Regulation 2010. Moreover, the U-value of facades used in the notional building in the UK's National Calculation Methodology is $1.6 \text{ W/m}^2\text{K}$, which suggests that it is better to use lower U-value facades. The high performance curtain wall products are developed and can achieve a U-value of $1.1 \text{ W/m}^2\text{K}$, which is well below than the U-value limit in the Building Regulation and the notional building façade's U-value.

These low U-value products use high performance insulation materials in the spandrel area to achieve low U-value while retaining the thinness. New insulation materials include vacuum insulation, aerogels, graphite doped products and various composites which have significantly lower thermal conductivities. In the vision area, high performance glazing, windows with frames made of fibre-reinforced composites, phase change materials, etc, are used (Rode 2012). High performance glazing in particular

uses various coatings which can better control the solar heat gain, increase the insulation level and enhance visible light transmission. Other innovative sustainable materials such as timber, and composites materials are also incorporated into the facades.

Another popular facade system is the double skin facade which has two glazed surfaces with a central cavity. It can be a sealed box or open to air circulation, therefore affecting the air temperature inside the facade. The outer layer must be high resistance laminated glass but the inner layer does not have to be fully glazed. This facade system is complex and is studied by many researchers (Alberto et al. 2017). The disadvantages of double skin facades are higher initial cost (Keeler and Burke 2009), and sometimes a high amount of energy is used to ventilate and control the air space between the layers.

Other new technologies include solar panels, solar wall (Stazi et al. 2012), dynamic walling systems and switchable glass which can be incorporated into curtain walls are developed to improve the energy performance of buildings.

The rest of this section focuses on the developments for 'single skin facades' to enhance their thermal performance, i.e. lowering their U-value and g-value.

2.2.3 High performance insulating materials

Today, the main research focus on curtain walls is still on achieving low thermal conductivities. One type of high performance curtain wall involves using high performance insulation materials in the spandrel areas. High performance insulation materials allow the spandrel areas to achieve a low U-value while being very slim.

The state-of-the art insulation materials which could be used instead include vacuum insulation panels, gas-filled panels, aerogels and phase change materials. Traditional insulation materials such as mineral wool, cellulose, expanded polystyrene and extruded polystyrene are thick and hence not desirable in curtain wall systems. Figure 2.9 shows some of the traditional insulation materials and the vacuum insulation panel. Figure 2.10 shows the thickness of different insulation materials. Out of these, vacuum insulation panels and aerogels would appear to have promising futures. These materials can achieve a very low U-value and at the same time are thin. They provide the design flexibility desired by architects and can potentially make a big contribution towards the zero carbon ambition. However, each of these advanced materials has

their own shortfalls. Hence, one needs to understand their performance limitations in order to optimise performance (Jelle 2011).

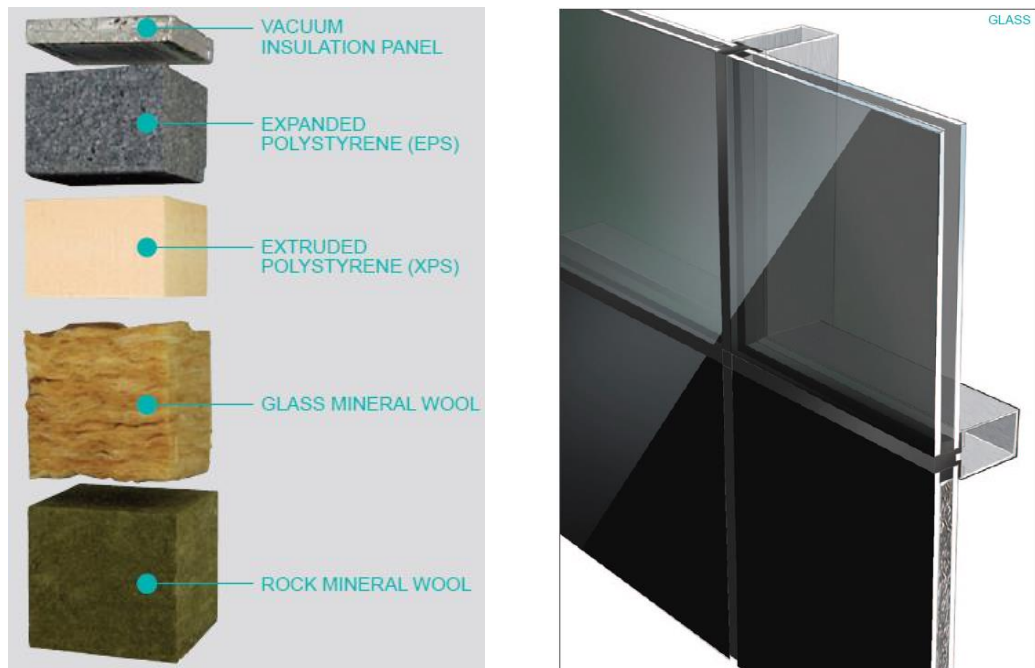


Figure 2.9 Traditional insulation material, vacuum insulation panel and high performance curtain wall unit (Dow Corning products)

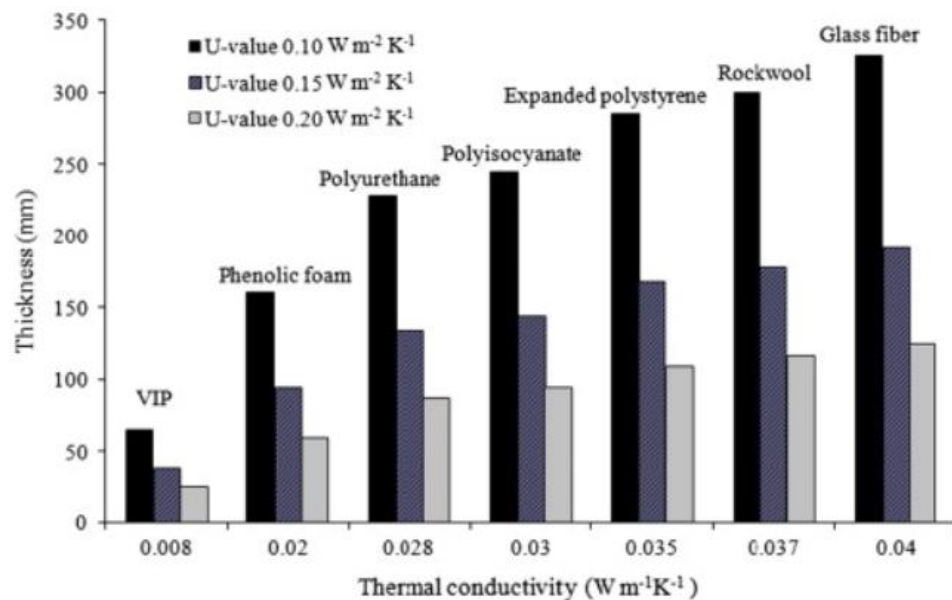


Figure 2.10 Thicknesses of different insulation materials required to achieve different U-values (W/m²K) for a typical masonry cavity wall with a U-value 0.53 W/m²K

a) Vacuum insulation panels

Vacuum insulation panel (VIP) consists of an open pore core material, for example, fumed silica and water vapor tight foil wrapping. Because of their low thermal

conductivity, vacuum insulation panels are now becoming increasingly used in building works, especially the manufacture of high performance curtain walls. 20mm VIP can achieve a U-value of $0.88 \text{ W/m}^2\text{K}$ which is similar to 90mm of mineral wool insulation. It is thought to be one of the solutions towards achieving the 'zero carbon' building ambition. Some manufacturers have already combined vacuum insulation panel with high performance glass. The resulting curtain wall system can achieve U-values as low as $1.1 \text{ W/(m}^2\text{K)}$ with a 50% vision area.

Shortfalls include that VIPs cannot be cut to size on site because of the air-tight wrapping. The thermal conductivities of VIPs range from 3-4 mW/mK in pristine condition and 8 mW/mK after 25 years due to water vapour and air diffusion. Therefore, manufacturers need to guarantee their lifetime quality and also to extend their life time (Kalnæs et al. 2014). A new concept is being developed: vacuum insulation material which is homogeneous and can overcome the durability problem (Jelle et al. 2010). Further problems include the high cost of the material, lack of certified building systems and official approvals from government agencies.

Vacuum insulation panels development is still at its early stage - they have been on the market for less than two decades. Although the initial results are good, more monitoring data is needed to establish their long term performance. Early results show that they are good at reducing energy usage but there is insufficient data to draw firm conclusions regarding their life cycle performance. Therefore, more data is needed to reduce the uncertainty for larger commercialization of this product.

b) Aerogels

Other high performance alternative materials which are also available include aerogels and nano insulation materials (Baetens et al. 2011). Aerogels are dried gels with a very high porosity and very low thermal conductivities. They can be used in the opaque wall to improve its U-value. Translucent or transparent aerogels can be installed in between two glass layers because they can allow diffused light enter the indoor space and at the same time improve heat insulation.

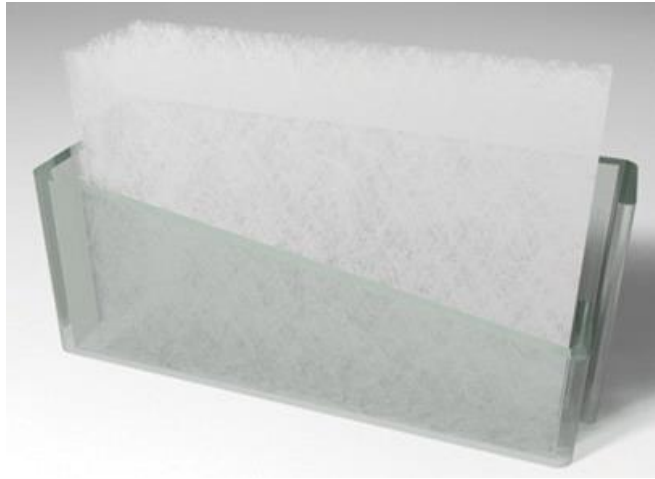


Figure 2.11 Aerogel

c) Adaptive insulations

Dynamic insulation can modulate the amount of heat transfer across the building envelope, admitting desirable heat gains while reducing unwanted heat losses in winter, or increasing the desired heat losses summer while preventing unwanted heat gains. Therefore dynamic insulation in the building envelope could enhance the indoor thermal environment and simultaneously reduce energy demand in buildings. Dynamic insulation products include translucent element switchable U-value which varies the U-value by allowing convection in the air space of the facade, variable pressure vacuum insulation panels or variable pressure aerogel blanket of which U-value changes due to the change in pressure (Pflug et al. 2015). These technologies are in their early stages and more effort is needed to control the U-value of the product. Furthermore, Favoino et al. (2017) provided a good review of the development of adaptive insulation. The author pointed out that the control strategies of adaptive façade is the key to buildings' reduce energy usage; although adaptive insulation's performance has the potential to reduce building energy use, its performance is not yet thoroughly understood. Loonen et al. (2013) reviewed a number of the real examples of buildings using adaptive facades, however the author found the literature on these buildings limited.

2.2.4 Developments of glass technologies

Windows affect the thermal load of buildings mainly through two of their properties namely thermal transmittance (U-value) and solar energy transmittance (g-value). This section reviews the technologies that have been employed in the window system to enhance its thermal performance and the ability to reduce solar heat gain in order to improve the energy performance of buildings.

a) Windows' basic properties

The thermal transmittance (U-value), of a window is a combination of the effects of the U-value at the center of the glass pane, its frame and the interaction between the glazing and the frame. The overall window U-value determines the amount of conductive heat transfer allowed through the window.

Total solar energy transmittance (g-value) is defined as the fraction of solar radiation at near normal incidence that is transferred through the glazing by all means. It is composed of the direct transmittance, also known as the short wave component, and the part of the absorptance dissipated inwards by longwave radiation and convection, known as the longwave component. The proportions of the absorbed energy that are dissipated either inside or outside depend on the glazing configuration and the external exposure conditions. While solar radiation in the visible wavelengths is largely transmitted through glass, the far-infrared radiation from terrestrial objects is not transmitted. It is mostly absorbed, warming up the glass. The warm glass then reradiates the energy, some to the interior and some to the exterior. Figure 2.12 shows the scheme diagram of glazing system heat transfer.

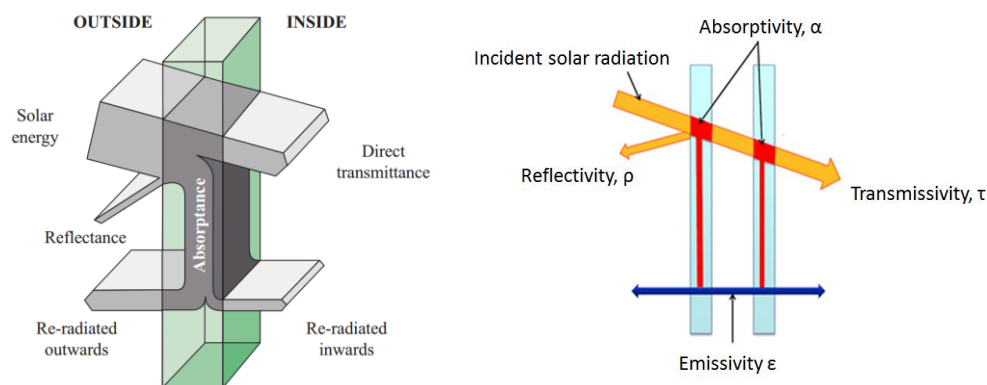


Figure 2.12 Glazing properties

$$\alpha + \tau + \rho = 1 \quad \text{Equation 4}$$

α absorptivity or Solar Energy Absorptance (EA) is the proportion of solar radiation at near normal incidence that is absorbed by the glass

ρ reflectivity Solar Energy Reflectance (ER) is the proportion of solar radiation at near normal incidence that is reflected by the glass back into the atmosphere.

τ transmissivity or **Direct Solar Energy Transmittance (ET)** is the proportion of solar radiation at near normal incidence that is transmitted directly through glass

ϵ , the emissivity of glass, determines the amount of absorbed energy then radiated by the glass.

The intensity of the incident radiation and the angle of incidence between the solar beam and the glazing surface determine the amount of solar radiation transmitted and absorbed. Table 2.5 shows the properties of some of ‘sun-controlled’ glazing available in the market. It can be seen that with the current technologies, low g-value glazing is achievable.

Product Description	Light		Solar Radiant Heat				Shading Coefficient			U _g -value (W/m²K)
Outer Pane	Transmittance	Reflectance	Direct Transmittance	Reflectance	Absorptance	Total Transmittance (g-value)	Short Wavelength	Long Wavelength	Total	Argon (90%)
Pilkington Insulight™ Sun (with 6 mm Pilkington Optifloat™ Clear inner pane and 16 mm 90% argon filled cavity – unless otherwise indicated)										
Pilkington Suncool™										
6 mm 70/40	0.70	0.10	0.38	0.28	0.34	0.42	0.44	0.04	0.48	1.1
6 mm 70/35	0.69	0.16	0.34	0.35	0.31	0.37	0.39	0.04	0.43	1.0
6 mm 66/33	0.65	0.16	0.32	0.35	0.33	0.36	0.37	0.04	0.41	1.0
6 mm 60/31	0.59	0.11	0.28	0.32	0.40	0.32	0.32	0.05	0.37	1.0
6 mm Silver 50/30	0.49	0.39	0.28	0.43	0.29	0.31	0.32	0.04	0.36	1.0
6 mm Blue 50/27	0.49	0.19	0.25	0.35	0.40	0.28	0.29	0.03	0.32	1.1
6 mm 50/25	0.49	0.18	0.24	0.33	0.43	0.27	0.28	0.03	0.31	1.0
6 mm 40/22	0.39	0.20	0.19	0.35	0.46	0.23	0.22	0.04	0.26	1.1
6 mm 30/17	0.30	0.25	0.15	0.37	0.48	0.18	0.17	0.04	0.21	1.1
Pilkington Suncool™ OW (with 6 mm Pilkington Optiwhite™ inner pane and 16 mm 90% argon filled cavity)										
6 mm 70/40	0.73	0.10	0.44	0.39	0.17	0.45	0.51	0.01	0.52	1.1

Table 2.5 Performance Data Pilkington Insulight Sun with 6mm Pilkington Optifloat Clear Inner Pane

As shown in Table 2.5, there are a few other derived parameters that are commonly used when specifying window products. A shading coefficient (SC) is also used and is the amount of directly transmitted and absorbed energy transferred to a space through a piece of glass compared to a standard piece of 3mm clear float glass at the same conditions. The relationship between the shading coefficient (SC) and the solar heat gain coefficient (SHGC) is $SC = SHGC \text{ of glass} / SHGC \text{ of 3mm clear glass} = SHGC / 0.87$. (Al-Waked 2010). It comprises a short wavelength and long wavelength shading coefficient. The short wavelength shading coefficient (SWSC) is the direct energy transmittance divided by 0.87. The longwavelength shading coefficient (LWSC) is the fraction of the absorptance released inwards, again divided by 0.87. The visible

light transmittance (VLT) is the amount of visible light transmitted through the glass (Kim 2011).

b) Improving window thermal performance

Windows are conventionally thought as a building envelope element that can lose a lot of heat energy due to the high U-value of a glass pane. However, with current technologies there are good insulated windows and it is possible for them to outperform opaque walls in terms of thermal performance. Large office buildings are likely to require low g-value glasses because of high internal load, although this will depend upon specific usage of the structures as well as climate.

i) Multi-pane glasses to improve U-value

Traditionally, windows are single pane glasses and can lose a lot of heat because of its high U-value. With the growing desire of having larger area of windows, limiting the heat loss through windows became crucial. Gradually, double glazing, triple even quadruple glazing are becoming available in the market. The sheets of glass are separated by a spacer and sealed to form a single glazed unit with an air space between each sheet. Different types of gas are used in between double panes to improve its U-value, they can be argon filled or air filled (Rezaei et al. 2017). Increasing the number of glass panes can decrease the U-value and solar energy transmittance due to more number of gas-glass interfaces.

ii) Low emissivity glasses

Glasses with low-emissivity coatings are a type of energy-efficient glasses designed to reduce heat loss to the cold outdoor. It allows the passage of the short wave radiation from the Sun. However, the invisible coating increases the reflectance of long wave infra-red radiation back to the interior by reducing the emissivity of the glass (its long wave infra-red absorption). e.g. Pilkington K Glass. It is often used in multi-pane glasses. In a warm climate it can reflect the long wave radiation back to outdoor (Pilkington 2017).

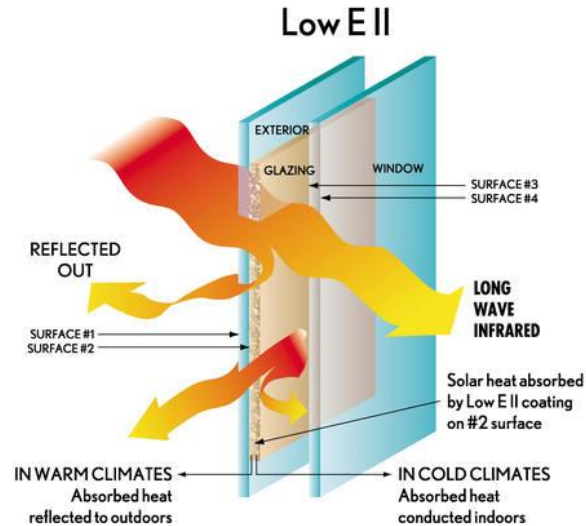


Figure 2.13 Low emissivity double glazing scheme diagram

iii) Reflective glasses

Reflective glasses have metallic coatings that can reflect away solar radiation. This type of coating provides a one-way mirror effect, preventing visibility from the outside. They are primarily used in non-residential buildings.

iv) Tinted glass

Tinted glass is a clear glass with some metal components added during the manufacturing process. The ratio of these metallic colorants affects the colour and optical properties of the glass. Tinted glass has lower solar transmittance and also decreases light transmittance. In addition, it warms up and reradiates the heat inside. Glass can be tinted to green, bronze or grey depending on the types of metallic colorant used however it does not mean that darker tints reject more solar heat than lighter ones. Tinted glass is common in non-residential buildings.

v) Advanced coatings and smart windows

Rezaei et al. (2017) summarised the latest developments in advanced window coatings and smart window materials. Windows' visibility can be enhanced by self-cleaning and anti-reflective coatings. Thermochromic materials change their light transmittance and solar control properties with temperature variation. Electrochromic materials work for the similar purpose but a voltage is applied to change their optical and solar properties. Suspended particle (SP) windows and liquid crystal windows (LC) can become transparent when a voltage is applied to them, otherwise they are translucent and reduce the light transmission. Phase change materials (PCM) have high thermal

storage which can be used to decrease energy demand in peak hours by absorbing the heat and then release it later. The advantages and disadvantages of each of these and some more traditional window systems are summarised in Table 2.6 which is extracted from Rezaei et al. (2017) work.

These window systems are complex, there is ongoing research to further develop these window technologies. Rezaei et al. (2017) only gave very broad recommendation on the application of these systems based on their U-value, g-value and visible transmittance. For example, lower U-value ($<2.5 \text{ W/m}^2\text{K}$) and high g-value (>0.5) should be used in cold climate/heating dominating places whereas higher U-value ($<4 \text{ W/m}^2\text{K}$) and low g value (<0.4) should be used in hot climate where cooling is dominating. Visible light transmittance is recommended to be around 0.7 for cold climate, 0.6 for hot climate. However, these general recommendations are not specifically for office buildings.

Glazing technology		Benefit	Drawback
Static	Tinted glass	<ul style="list-style-type: none"> Decreases glare 	<ul style="list-style-type: none"> Absorbs solar energy and releases heat into the building Decreases visible transmittance Decreases visible transmittance
	Reflective coating	<ul style="list-style-type: none"> Decreases glare Reflects NIR radiation 	<ul style="list-style-type: none"> Decreases <i>SHGC</i> (should be high for cold climates)
	Low-E and solar control coating	<ul style="list-style-type: none"> Reflects NIR or IR radiation Reduces heat reradiation by the window 	<ul style="list-style-type: none"> Increases <i>SHGC</i> (should be low for hot climates)
	Anti-reflective coating	<ul style="list-style-type: none"> Enhances visible transmittance 	<ul style="list-style-type: none"> Increases <i>SHGC</i> (should be low for hot climates)
	Self-cleaning coating	<ul style="list-style-type: none"> Visibility is maintained for longer time (due to self-cleaning) 	
	Aerogel	<ul style="list-style-type: none"> Exceptionally low thermal conductivity Glare reduction 	<ul style="list-style-type: none"> Translucent
Passive	Multiple-pane glazing	<ul style="list-style-type: none"> High insulating properties (low thermal conductivity, noise reduction) Can be used to combine various technologies for desired properties 	<ul style="list-style-type: none"> Occupy considerable space (especially for triple and quadruple glazing) Expensive
	PCM	<ul style="list-style-type: none"> Reduces building environment thermal fluctuation 	<ul style="list-style-type: none"> Translucent Needs a chamber since it turns into liquid Low visibility Solar modulation is not substantial Activation temperature is high
	Thermochromic	<ul style="list-style-type: none"> Reduces glare Reflects NIR radiation Reduces <i>SHGC</i> 	
Active	Electrochromic	<ul style="list-style-type: none"> Solar modulation Glare control 	<ul style="list-style-type: none"> Expensive Limited modulation levels Long response time relative to other active systems Needs electrical energy for transparency modulation (very low) Relatively Low <i>SHGC</i> for cold climates Is not commercialized; however, first four drawbacks of conventional EC still hold
	Spectrally tunable EC	<ul style="list-style-type: none"> Independently modulation of NIR and visible spectra <i>SHGC</i> may be controlled without affecting visible transmittance Useful for various climates Glare control 	<ul style="list-style-type: none"> Very low visible transmittance
	PV EC	<ul style="list-style-type: none"> Solar modulation Glare control Self-powered 	
	Gasochromic	<ul style="list-style-type: none"> Solar modulation Glare control Faster response time relative to EC Simpler layer structure than EC 	<ul style="list-style-type: none"> Not commercialized yet Needs special equipment (electrolyser) and electrical energy for operation
	SP	<ul style="list-style-type: none"> Solar modulation Glare control Fast response time Vast transparency levels 	<ul style="list-style-type: none"> Needs electrical energy for maintaining transparency levels (except fully tinted) Electric power consumption is higher than EC but still low Relatively low <i>SHGC</i> for cold climates expensive
	LC	<ul style="list-style-type: none"> Glare control Becomes translucent (for privacy applications) 	<ul style="list-style-type: none"> Needs electric power for remaining transparent Cannot modulate <i>SHGC</i>

Table 2.6 Advantages and disadvantages of different glazing types (Rezaei et al. 2017)

2.2.5 Solar shading

The effect of solar shading is that it reduces the solar heat gain from the sun and in turn the cooling needs, it is particularly useful in high rise offices with large window areas where there is high cooling demand.

Shading can be achieved by a wide range of building components including interior or exterior elements such as blinds, louvers, overhangs, side fins and balconies. Kolokotroni et al. (2004) studied a few types of typical solar shading in high rise offices. Internal and external blinds and found them beneficial in UK offices. Shading are widely studied by many researchers all over the world, such as Valladares-Rendón et al. (2017) who provided a review of the solar shading system available.

However, the use of solar shading needs to be carefully balanced with lighting and heating demand. As the sun is shaded, there is reduced amount of natural light and this causes increases in heating demand in heating seasons.

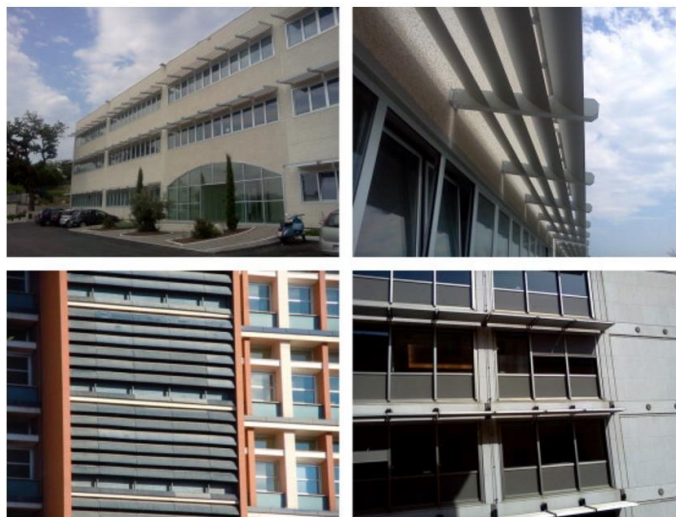


Figure 2.14 Typical solar shading devices (Bellia et al. 2013)

Grynning et al. (2014) studied the solar shading control strategies in offices in cold climates. Given offices often have large glazed areas exposed to solar radiation, which can lead to large cooling demands during hot periods. However the solar radiation can help reducing heating demands during cold periods. Shading control strategies which are only activated depending on the air temperature, cooling, glare have been developed to enhance their performance. Lai et al. (2017) suggested that switchable and adjustable shading devices of which the operation depends on occupancy behaviour might have a better performance than static shading. Karlsen et al. (2016)

studied solar control strategies in cold climates for venetian blinds. It might not be favourable in winter.

Therefore, shading works to control the solar heat gain, its purpose is similar to windows' solar control introduced before. Other disadvantages of utilising solar shading are aesthetic and cost.

2.2.6 Framing materials

Commercial curtain wall frame are mostly made from metals, which are highly conductive. Aluminium frames have been widely applied in curtain walling systems. A high-performance curtain wall should incorporate a thermal break to prevent heat transfer from one side of the wall to the other via conduction through the frame material. Systems with a thermal break separate frame components into interior and exterior pieces and use a less conductive material to join them. The frame must be properly detailed and installed to prevent thermal bridging. The performance of a thermally broken frame can be short circuited if it is attached to other building components in a way that creates a thermal bridge. Carbon fiber reinforcement frames are now starting to be used and might replace aluminum frames in the future.

2.2.7 Complex facade design

The early stage of facade development is very much linked with the way in which society flourished. More and more complex buildings were required, therefore the main built form shifted from conventional load bearing wall to thin curtain wall structures. Recent developments of facade design are more due to the environmental impact of buildings.

One way to achieve the low carbon and low energy buildings are using high performance insulation and glazing materials in curtain walls. These advanced technologies enhance the U-value and g-value of curtain wall.

While these new facade materials and technologies seem to have promising futures, the exact energy saving potential is unclear. For example, Al-Waked (2010) pointed out that high performance glazing can reduce the peak cooling load. However, a more moderate performance glazing results in the best overall performance. Window size decides the amount of day lighting and solar heat gain. Another example is that maximum daylight is desired because it can save lighting energy but at the same time one needs to be careful with solar heat gain control. Glare is also a problem.

Some of these technologies can contradict each other and this proves the complex nature of facade design. A careful balance is needed to achieve an optimum solution. Other aspects which need to be considered are: cost, construction (installation), weight, durability, availability, comfort and aesthetic qualities.

The next section provides extensive literature reviews of past studies done on facades parametric studies in order to investigate whether these new technology will help achieve the low carbon and low energy office ambitions.

2.3 Benefits of high performance facade in hot and cold climate

The effect of U-value of building envelopes and g-value of windows has been assessed by many researchers all over the world. Different opinions arise about the effectiveness of superior insulation in both hot and cold climates. This section reviews the studies that have been carried out on office buildings in cold/cool climate and warm/hot climates. These studies appear to provide conflicting results.

2.3.1 Cold climates

Grynning et al. (2013) investigated the influences of the U and g-values of the windows on the heating and cooling demand of a three storey office in Oslo, Norway. The state-of-the-art windows available were four-pane glazing units which could reach U-values of $0.4\text{W/m}^2\text{K}$ with SHGC value of around 0.3. In the study, the window's U-value was varied between $0.2\text{ W/m}^2\text{K}$ to $1.2\text{ W/m}^2\text{K}$, the lower bound was the U-value of a hypothetical five-pane window and the upper bound U-value was the limit in the Building Regulations. The U-value of opaque wall was set constant at $0.15\text{ W/m}^2\text{K}$. The assumed window-to-wall ratio was 0.55, therefore the overall U-value of the facade was between 0.18 to $0.73\text{W/m}^2\text{K}$. The window's g-value was varied between 0.2 to 0.8. Figure 2.15 shows the effect of varying g-value and U-value during heating and cooling seasons separately. It can be seen that during the heating season, the facade with a lower U-value and a higher g-value required less heating demand. This conforms to the conventional thinking. When there was a cooling requirement in the office, the facades with a higher U-value and smaller g-value performed better. Annually, as shown in Figure 2.16, that the windows with the lowest U-value of $0.2\text{W/m}^2\text{K}$ and SHGC of 0.4 has the best performance. The SHGC should not be lower than 0.4. The effect of lowering U-value is more obvious when SHGC are lower.

Overall, in offices in Oslo, a reduction of the window U-value from 1.2 to $0.8\text{ W/m}^2\text{K}$ (i.e. going from a double glazing to a triple pane insulated glazing unit) can reduce the energy demand for heating and cooling between 5-15% depending on the SHGC. Lower U-value facades reduce the heating demand but increase annual cooling demand. It was found that cooling load was high despite the cold weather condition; this might also be due to the fact that the U-values used in the study were extremely low. The study also pointed out that adding dynamic solar shading can lower the energy demand further.

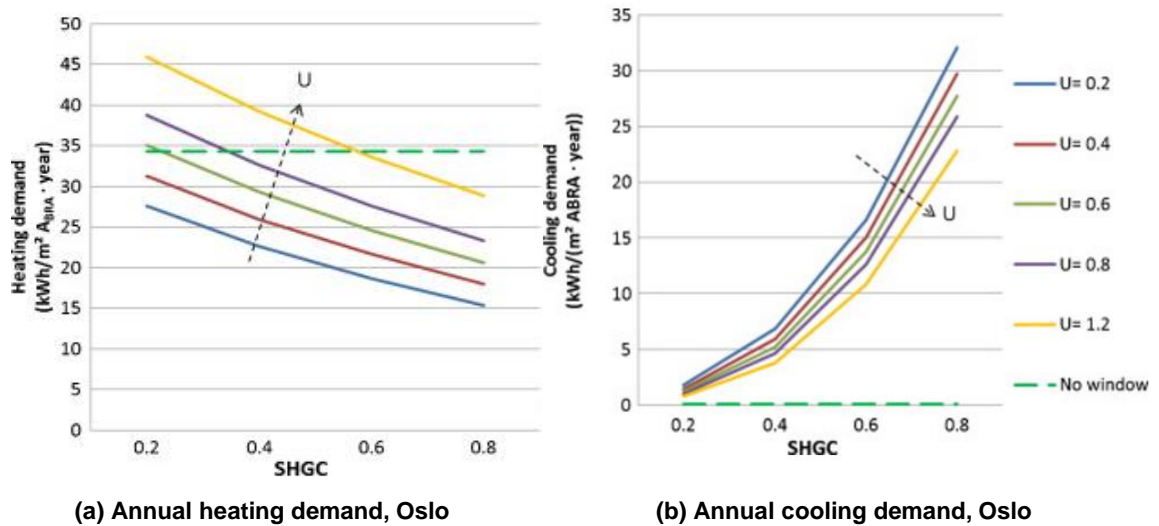


Figure 2.15 Heating and cooling demand of buildings using different window types for Oslo climate, Energy Plus (Grynning et al. 2013)

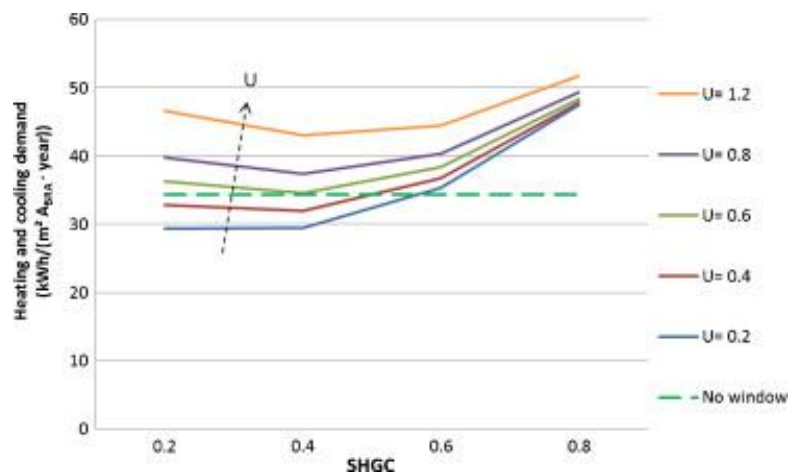


Figure 2.16 Combined sum of heating and cooling demand for office building ($\text{kWh/(m}^2 A_{\text{BRA}} \cdot \text{year)}$) for Oslo climate, Energy Plus (Grynning et al. 2013)

Driven by the nearly zero energy targets required by European Union, Thalfeldt et al. (2013) was looking for cost optimal as well as energy efficient facade solutions in the cold climate of Estonia. Window properties, external wall insulation, window-to-wall ratio (WWR) and external shading were considered. Energy and daylight simulations were performed. It was found that because heating was the dominating load, the energy optimal solution was to increase the number of window panes with low emissivity coatings to achieve low U-values. Table 2.7 summarises the energy efficient designs for 4 types of windows. Dynamic external shading only shows positive effect in East and West orientations; however it is not an economical solution. Cost optimal solution would be highly transparent triple low emissivity glazing with lower window to wall ratio (S,E,W: 0.24, N: 0.37),. High performance quadruple glazing is good

alternative to pricey quintuple glazing since the energy performance from 4 to 5 is marginal.

Window type	Notes	
double/ $U_{\text{window}} > U_{\text{wall}}$,	minimum WWR (0.22) as the lighting requirements allow	the effect of lighting is smaller than that of U values
triple glazing	minimum WWR (0.24) as the lighting requirements allow	
quadruple	minimum WWR does not have advantages, WWR = 0.4	
quintuple glazing, U_{window} can be similar as U_{wall}	advantages, WWR = 0.6 respectively,	saving in lighting energy and heating energy may compensate the potential rise in cooling energy, more expensive to build

Table 2.7 Facade design strategies in the cold climate of Estonia(Thalfeldt et al. 2013)

Pikas et al. (2014) confirmed the desire to improve the office buildings' insulation levels in cold climates like Estonia. The study investigated a generic single floor of an office building in Estonia where the climate is cold. The study found that the most cost and energy efficient facade would be one with a small window to wall ratio, argon filled triple glazing and walls with 200 mm thick insulation with a U value of 0.16 W/m²K.

Glass windows are responsible for 40 billion dollars in energy loss in US buildings annually. Kim (2011) investigated the energy efficiency of high performance glazing materials which are referring to low-e coated or heat reflective glass, solar control films, surface treatments, laminated glass with a high performance interlayer. The work compared the life cycle energy consumption of a glass curtain wall system with a transparent composite facade system which is believed to be a more sustainable alternative. A life cycle assessment was performed for each of the facade systems in order to assess the energy and CO₂ in pre-use, use and post use phase. EQuest which is an energy simulation program was used to estimate the heating, cooling and lighting load of a building using each of these wall systems. The author suggested that in cold climate, the key principle is to minimize the U factor and optimize SHGC and visible light transmittance.

Raji et al. (2016) investigated the facade design strategies in high-rise offices in the Netherlands where the climate is temperate, with cool summers and mild winters. Four measures which included glazing type, window-to-wall ratio, sun shading and roof strategies were studied. The results showed that heating was dominant and the use of high performance facade reduced the annual heating demand by a large fraction

although increased the annual cooling load by a small amount. Overall, high performance envelope offered energy saving by around 42% for total energy use, 64% for heating and 34% for electric lighting.

Boyano et al. (2013) analysed potential energy demands saving of lighting control, lower U-value facades and building orientation in three European cities, namely Tallinn, Madrid and London. Window U-value is lowered from 3.16 to 1.78 W/m²K and wall U-value was varied between 0.12 to 0.66 W/m²K, hence the tested overall U-value of the facades. The author confirmed that lower U-value facades can reduce energy demand for heating and cooling for cold places such as Tallinn and also in London.

However, the effect of lowering the U-value of facade in offices London or UK is clear. For example, Kolokotroni et al. (2004) created a database of 150 results based on different combinations of facade systems, office building types, level of internal gains. The work looked at the impact of facade systems on office buildings' energy demand and environmental performances in the UK. A number of generic office building facade types including lightweight cladding, heavy weight cladding and curtain walls. Two construction standards (standard and high-quality which has a lower U-value) were compared. Other varying building parameters are office types (naturally ventilated open-plan or air-conditioned prestige office), solar shading. The internal environmental conditions were set separately for these two types of offices. Figure 2.17 summarises the varying parameters. A model of a single office space (6m deep, 10m long, 3m high) with a single face external facade is used in the energy simulation program. The aspects under comparisons are: heating/cooling energy demand, comfort temperature, daylight factor and environmental impact. Figure 2.18, Figure 2.19 are the cooling energy demand and heating energy demand of buildings using different facade types for air-conditioned office scenario. In air-conditioned offices, the combined effect of improving the standard of the facade and reducing internal heat loads is shown to be able to reduce the environmental impact by 22% and reduce the cooling demand by 35%. Although the author assumes improving the construction of facade which is lowering U-value is beneficial, the standalone effect of improving U-value of facade is not studied. The curtain wall has the largest cooling demand because of the high glazing ratio. The overall results showed that the above mentioned parameters all affect a building's performance energy and environmental performance. The author pointed out that there is a need for an early facade design tool to assist designers to make choices of environment friendly facade.

The curtain wall tested in the study has a U-value of 1.6 W/m²K and with window to wall ratio of 0.85.

Part of reference	Code	Description
Building type	nv	type 1 building with natural ventilation
	ac	type 2 building with mechanical ventilation
Energy conservation	g	good energy use
	t	typical energy use
Facade code	cw	curtain wall
	br	masonry cladding
	cl	lightweight metal cladding
	rs	heavyweight concrete cladding
	ds	double-skinned-facade
Facade standard	1	standard system
	2	high quality system
Shading code	0	no shading
	1	horizontal overhang
	2	horizontal glass louvres
	3	horizontal metal louvres
	4	vertical metal louvres

Figure 2.17 facade types and code (Kolokotroni et al. 2004)

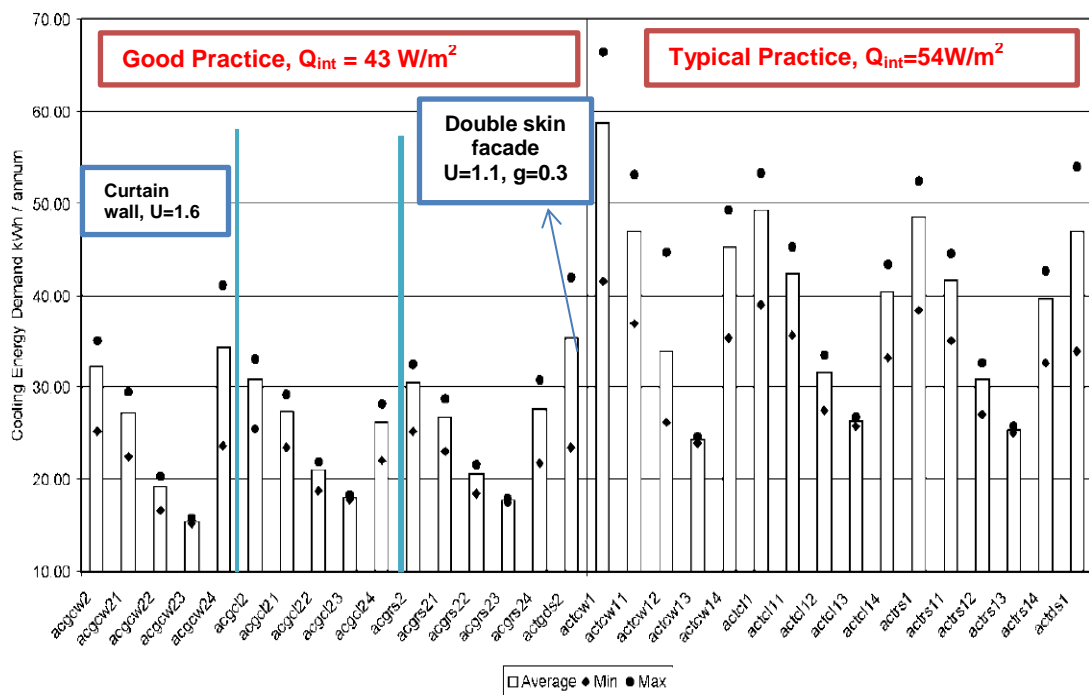


Figure 2.18 Cooling energy demand in an air-conditioned office (Kolokotroni et al. 2004)

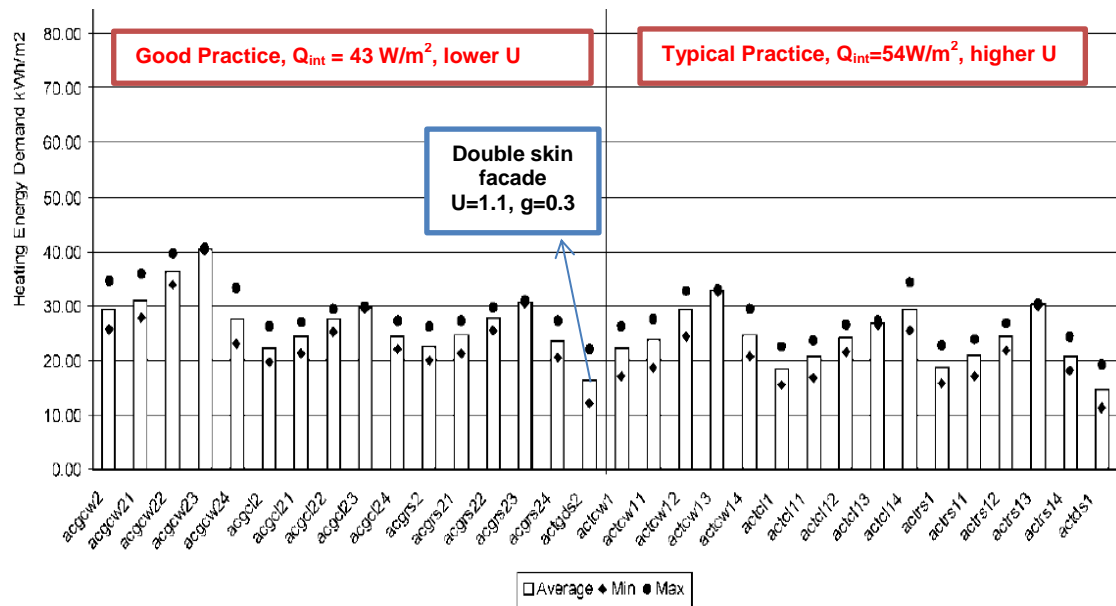


Figure 2.19 heating energy demand in an air-conditioned office (Kolokotroni et al. 2004)

Furthermore, a study conducted by AECOM suggested that lowering U-value of facades from the recommend value of $2.2 \text{ W/m}^2\text{K}$ has little benefit (AECOM 2011).

Even in the adaptive insulation technology, the assumption is that heating is dominant in winter, then optimization process occur (Favoio et al. 2017). Jin et al. (2017) carried out a case study in Shanghai where the climate is temperate. Their study found that in a temperate climate like Shanghai where there is a balance of heating and cooling load , adaptive facade might be beneficial.

2.3.2 Warm climate

Prieto et al. (2017) reviewed cooling related research in office buildings from year 1990 to 2014 in order to support the design of sustainable office buildings in warm climates. The work pointed out that there is a growing research interest in cooling in offices. McMullan (2012) states that specifying envelopes with high insulation levels should reduce energy usage since this reduces heat infiltration. This is confirmed by the following studies.

For example, in Turkey, researchers have identified a lack of adequate insulation in the country and confirmed the energy saving effects of adequate insulation levels. Aktacir et al. (2010) assessed the impact of insulation thickness of extruded polystyrene in air-conditioned office building in Adana, Turkey. Adana is in Mediterranean region. It has hot and humid summer and warm winter. Three levels of insulation were considered and the overall U-values of wall were $0.403 \text{ W/m}^2\text{K}$ (A), $0.546 \text{ W/m}^2\text{K}$ (B) and 0.662

W/m²K (C). Wall with no insulation and had a U-value of 1.849 W/m²K was also analysed for comparison purpose. Design cooling load was found to have decreased maximum by 33% due to the thermal insulation. Figure 2.20 shows the ratio of the thermal insulation dependent loads to the total cooling load. It can be seen that Building A, which has the best insulation, has the lowest ratio, i.e. the best energy performance.

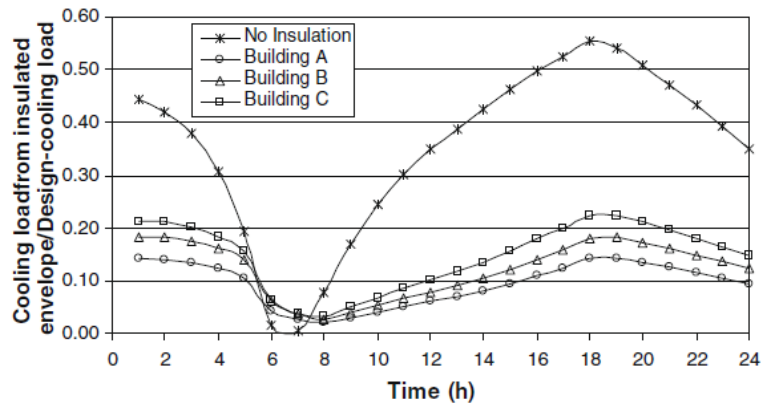


Figure 2.20 ratio of thermal insulation dependent loads to the total cooling load

In the city of Denizli, Turkey, Dombaycı (2007) used the degree-day method to assess the environmental impact of one of traditional insulation materials, the expanded polystyrene during the heating season. The work has found that as the thickness of the insulation layer goes up, the better the energy and environmental performances of the building. Optimum thickness, which is 0.095m is found at the lowest point of the total cost which is a sum of fuel cost and insulation material cost. The work concluded that buildings with optimum insulation thickness can achieve around 46% reduction in energy consumption and around 42% in CO₂ emissions. The result of this work gives a clear picture of the relationships between the insulation level and cost or energy, or environmental performance of the building as shown in Figure 2.21 and Figure 2.22. However, building type was not specified in this work.

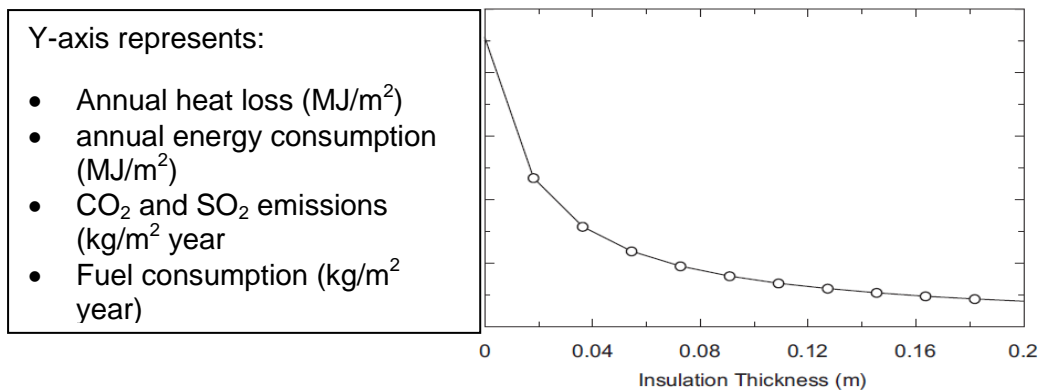


Figure 2.21 relationship between insulation thickness and annual heat loss, annual energy consumption, CO_2 and SO_2 emissions and fuel consumption (Dombaycı 2007)

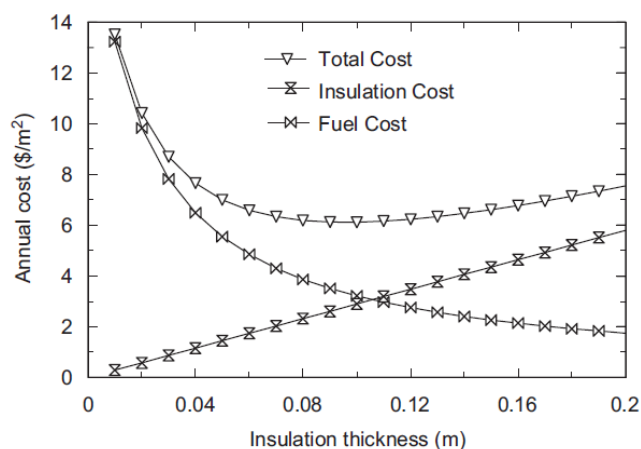


Figure 2.22 Optimum insulation thickness in terms of total annual cost (Dombaycı 2007)

Similar relationships and large reductions in energy and CO_2 emissions achieved by optimum insulation thicknesses in residential buildings from 16 cities in Turkey were found by Bolattürk (2006). Bolattürk (2006) also suggested that insulation calculation should be done separately for each city but not for a climate zone and the impact of energy saving is more significant when more expensive fuel is used.

Muhammad et al. (2016) found that using nano-vacuum insulation panel in wall and roof constructions, and nano-gel in windows instead of traditional construction could jointly reduce around 18% of annual energy consumption of an office building model in Dhahran, Saudi Arabia. The tested location has a hot and humid climate and the single storey building model is assumed to have a WWR of 0.25. The work showed that most of the reduction was contributed by replacing base model double glazing with $U=2.71 \text{ W/m}^2\text{K}$ and $g=0.75$ by nanogel glazing with $U = 0.45 \text{ W/m}^2\text{K}$ $g = 0.35$. 1% of improvement was made by VIP in wall which has an overall U-value of $0.06 \text{ W/m}^2\text{K}$ compared with base model wall with $U= 0.48 \text{ W/m}^2\text{K}$. The study also showed that the

change in relative humidity makes no difference but the change in the set-point temperature has a large influence on the optimum solution.

However, the effect of lowering the U-value of facades is not always positive in warm/hot climates. Masoso and Grobler (2008) analysed a typical three-storey office building using Energy Plus in Botswana, Africa, where the climate is hot and dry. The findings were at a certain combination of cooling-set temperature and internal gains in cooling season, there exists a 'point of thermal inflection' where 'higher the U-value the better'. The author also suggested a similar scenario may occur even in heating-dominated climates due to a combination of effects from the high usage of office equipment which generates heat, increased use of insulation, good thermal bridges, large glass areas, urban heat island effects and global warming which all contribute to heat gains.

Tsikaloudaki et al. (2012) carried out another study on assessing cooling energy performance of windows for office buildings in the Mediterranean Zone. Five cities were studied. The study found that when it is in cooling-mode, the U-value of windows shall not be below $2.00\text{W/m}^2\text{K}$. When clear glazing is used, optimum U-value is between $2\text{--}3.2\text{ W/m}^2\text{K}$, especially when window-to-wall ratio is high. The author found that advanced fenestration systems with extremely low thermal transmittance are unfavorable because they stop the dissipation of heat to the ambient environment and lead to higher cooling demand.

Kim et al. (2014) conducted a study of windows of office building in Korea and focused on the influence of two window parameters which are the window-to-wall ratio and SHGC on building energy consumption. The study compared the building design policies and guidelines of Korea and that of other countries. In Seoul, it was found that higher the U-value, lower the SHGC is beneficial.

A few authors who studied the cold climate also hinted that in warm climate the low U-value facades might not be beneficial. For example, the study conducted by Kim (2011) also suggested that in a warm climate, it is more critical to reduce the SHGC than enhance its U-factor. Boyano et al. (2013) concluded that an improvement of the thermal insulation of the envelope may not be the best recommendation due to the heat gains from office equipment and solar gains.

2.3.4 Implication of climates on facade design

It is clear that the effect of lowering the U-value depends on climatic conditions (Lam et al. 2008). For example, Yang et al. (2008) looked at building envelope designs in five major climate zones in China, namely severe cold, cold, hot summer and cold winter, mild, and hot summer and warm winter. The five cities selected for investigation were Harbin, Beijing, Shanghai, Kunming and Hong Kong (Figure 2.23). Real building envelope design data was also gathered from building surveys and compared with the local energy code and ASHRAE standard, as shown in Table 2.8. Although the real U-value is often higher than the building code, the U-value of real building and the building code varies with the climate. It can be seen that colder the climate, lower the U-value of building envelopes.

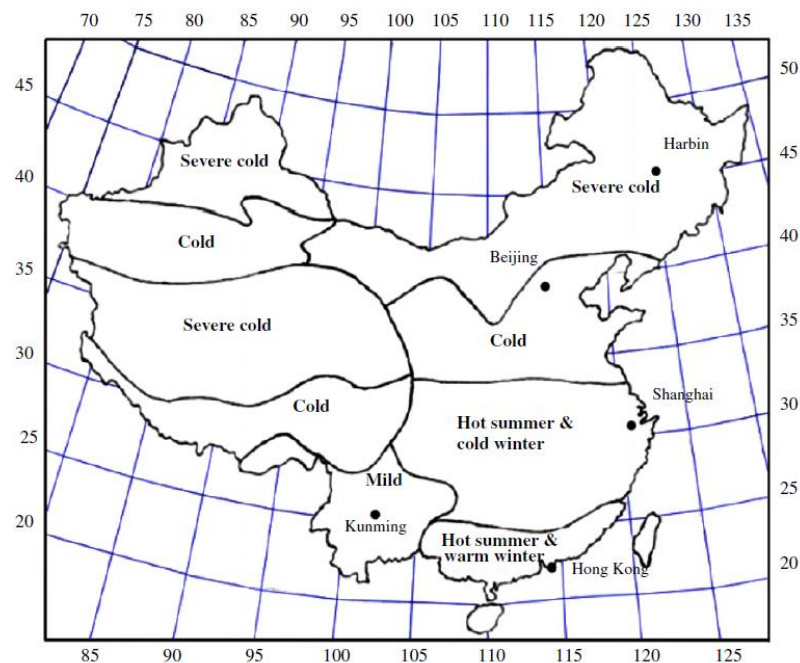


Figure 2.23 Geographical distribution of the five major climates and the five cities (Lam et al. 2008)

City	Climate	U values (W/m^2k)		
		Building Survey (average)	Local code	ASHARE
Harbin	severe cold	0.5	0.4	0.51
Beijing	Cold	1.05	0.5	0.86
Shanghai	hot summer and cold winter	1.51	1	0.86
Kunming	mild	1.63	1.5	3.29
Hongkong	hot summer and cold winter	1.7	2.01	3.29

Table 2.8 U-values for walls in five cities in china, from building survey and building codes

Aksamija (2015) summarised some general facade design strategies for energy efficient buildings in three major climate conditions: heating-dominated, cooling-dominated and mixed climates, as shown in Table 2.9. These guidelines conform with the general understanding of the influences of facade systems. However, although they help us to understand the broad strategies, they are not specific enough to unpick some of the confusion found in the literature regarding the benefits of low U-value façade in both cold and hot climate, as discussed in section 2.3.1 and 2.3.2..

Climate Type	Facade design strategies for energy efficient buildings
Heating dominated climates	<p>Solar collection and passive heating: collection of solar heat through the building envelope</p> <p>Heat storage: storage of heat in the mass of the walls</p> <p>Daylight: use of natural light sources and increased glazed areas of the facade, use of high-performance glass, and use of light shelves to redirect light into interior spaces</p>
Cooling-dominated climates	<p>Solar control: protection of the facade from direct solar radiation through self-shading methods (building form) or shading devices</p> <p>Reduction of external heat gains: protection from solar heat gain by infiltration (by using well-insulated opaque facade elements) or conduction (by using shading devices)</p> <p>Cooling: use of natural ventilation where environmental characteristics and building function permit</p> <p>Daylight: use of natural light sources while minimizing solar heat gain through use of shading devices and light shelves</p>
Mixed climates	<p>Solar control: protection of the facade from direct solar radiation (shading) during warm seasons</p> <p>Solar collection and passive heating: solar collection during cold seasons</p> <p>Daylight: use of natural light sources and increased glazed areas of the facade with shading devices</p>

Table 2.9 facade design strategies for energy efficient buildings under different climate conditions (Ajla Aksamija 2013)

Gap in the research

Widely accepted concept is ‘the lower the U-value the better’, especially in heating-dominated seasons and overall colder climates. However, in recent years, it is surprising to find that this concept is not always the case. There is confusion in both

cold and warm climate. In cold climate, although the use of low U-value facade is beneficial, there is a high cooling demand. The reason mostly being the distinctive nature of office buildings – they have high internal gains which might lead to overheating problems. Literature on the use of extremely low-U value facade in prestigious office buildings is limited.

Although it is generally clear that reducing the amount of solar heat gain by using low g-value facade or solar shading is beneficial in both hot and cold climates, its relation with U-value is not clear in temperate climate.

The studies conducted used different models and did not explain the reasons of different conclusions reached. In addition, different assumptions were made in these models. One needs a consistent method to unpick the reasons behind these apparent differences in findings regarding the energy performance of low U-value facades in offices.

Building facade design is developed at a very early stage of the design process. Detailed energy analysis is performed at a much later stage when one needs to decide servicing strategy. Given the significance of the influence of the facade, it is important to study their influence at the early stage.

Apart from the properties of facades and climate, there are other influencing factors such as built form, internal design conditions, internal gains and ventilation strategies. All of these parameters are inter-related. Therefore, in order to assess the overall energy performance of a facade, we need to analyse its performance in the context of the whole building. The next section introduces the effect of office built form on building energy performance.

2.4 Built-form

Built form includes aspect ratio, glazing ratio, number of floors, orientation, layout and size of a building. In the non-domestic building sector, the current building regulation does not include any requirements on built forms of buildings. The National Calculation Methodology in Building Regulation part L compares the carbon emissions of a proposed building with a notional building which has the same form. However, previous studies have shown that built form can have substantial impact on building energy performance and hence carbon emission reduction. For example, the 'Zero carbon non-domestic buildings' Phase 3 final report produced by AECOM looked at the relationships between carbon emissions and built-form and concludes that all of the sub-aspects of built form, i.e., shape, size and orientation have an significant impact on building energy demand. Whether built form should be included in the next building regulation is still a question for debate as it is not clear if this is worth to make the effort from the designers' viewpoint and may result in negative consequences (AECOM 2011).

Shape and size

Different office types often differ in their size. Size also determines the ventilation strategies used in the office. Smaller scale office buildings usually use natural ventilation whereas larger scale office buildings use HVAC systems to regulate the internal conditions. These building characteristics affect energy costs of buildings. Smaller scale offices tend to be converted from residential buildings. Refurbished office buildings tend to have more conventional types of facades. This project focuses on tall and air-conditioned offices.

a) Aspect ratio

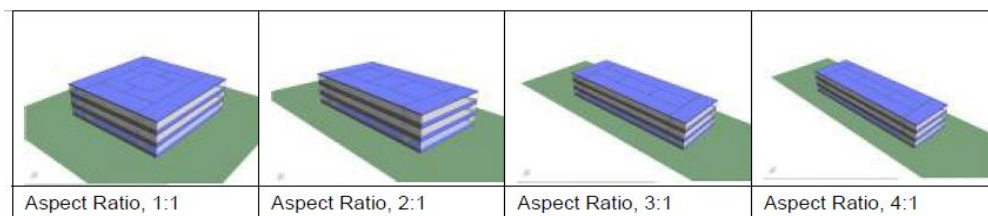


Figure 2.24 Aspect ratio of buildings (AECOM 2011)

Increasingly narrow floor plans increase daylighting which leads to a reduction in lighting energy use. However, it also results in an increase in both heating and cooling requirements (per m²) as they have a greater envelope per m² of floor area. Overall,

the carbon emissions only vary 2% across different aspect ratios with these two conflicting aspects. The main potential advantage of narrower buildings is that lower carbon strategies such as natural ventilation and mixed mode can be more easily adopted (AECOM 2011).

b) Number of floors

The AECOM report found that the highest CO₂ emissions occur in taller office block where emissions are 9% higher than from a single-storey building. This would imply that making buildings taller which increases daylight will increase emissions.

c) Shape coefficient

In a study by Yang et al. (2008), the relationship between the shape coefficient and office heating and cooling load was investigated as shown in Figure 2.25. Shape coefficient is the total office building envelope area to the space volume of a building inside the envelope. It is a combination effect of the aspect ratio and volume (no. of floors) of a building. Hence, a tall but narrow building will have a high shape coefficient. It was found that buildings with the same thermal performance walls would tend to have higher cooling loads. Same trend was found in winter. These results also suggest a difference between a typical floor and a top floor.

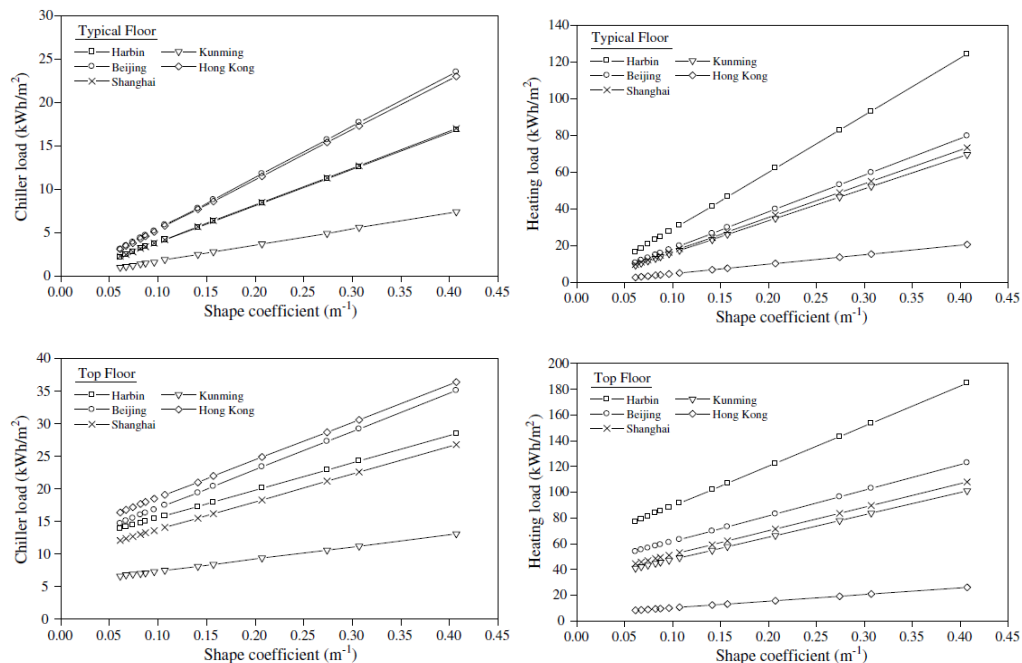


Figure 2.25 relationships between shape coefficient/ aspect ratio and heating/chiller load in offices (Yang et al. 2008)

Glazing ratios

Glazing ratios or window to wall ratios is the ratio of window area and wall area in a facade. It matters because it determines the amount of heat transfer through windows and walls.

Orientation

There are 8 principal orientations that building designers usually look at. They are North, North-east, East, South-east, South, South-west, West and North-west. In building energy analysis, orientation matters because the solar irradiation from the sun varies with the orientations which contribute to a large part of buildings' heat gains. In some locations, two principal orientations have larger impact than the rest, for example, north and south orientations are more critical in a lot of the Asia areas. However, depending on the purpose of the study, one can either explore the impact of all principal orientations or just the most influencing ones. In the UK, it is found that north/south generally have the lowest energy use of all possible orientations (AECOM 2011).

Layout

Korolija et al. (2013) developed an archetypal simulation model which represents variability in existing UK office building stock to be used in energy performance simulations for stock modelling and parametric studies. In this work, it summarised four types of major layouts found in the UK office building stock which are open-plan sidelit buildings (type 1), cellular sidelit (type 2), artificially lit open-plan buildings (type 3) and composite sidelit cellular around artificially lit open-plan buildings (type4) (Figure 2.26). Figure 2.27 shows the 3-D views of these four layouts built in Energy Plus which is a building energy simulation software. It can be seen in Figure 2.27 that the baseline models contain only one top floor, one ground floor and one intermediate floor. The number of intermediate floors can be changed by custom, however it was not considered to be a major influencing parameter on building energy performance. Apart from the built forms, other simulation parameters including building envelope properties, daylight and solar control measures and activity and operational related parameters (heating and cooling set points, ventilation rate, occupancy density and metabolic rate, equipment and light gain) are set at a few levels which are commonly used. Hence the archetypal model can represent 75% of the UK office building stock.

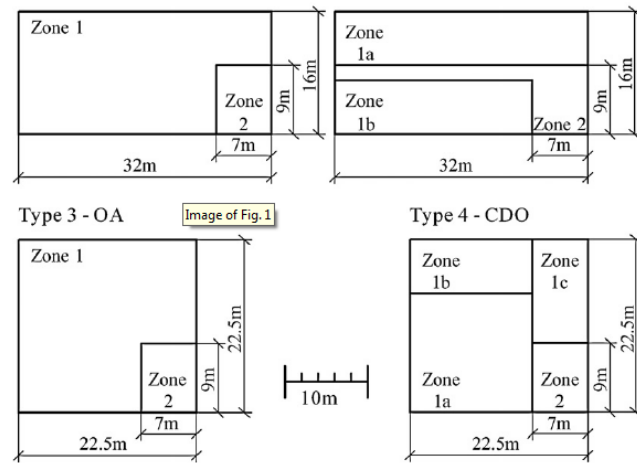


Figure 2.26 Office building model types (Korolija et al. 2013)

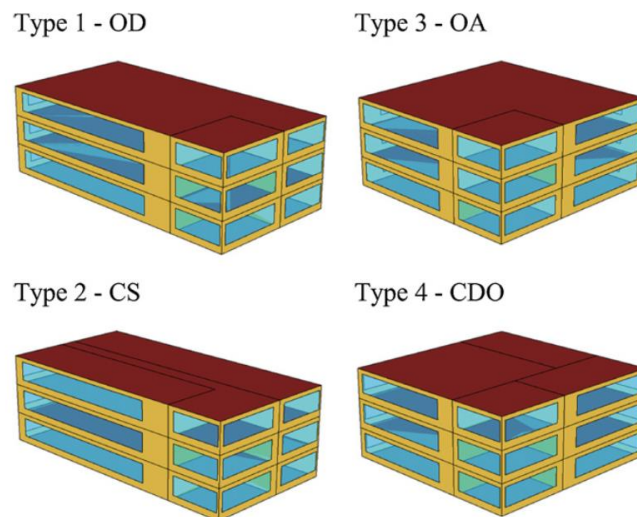


Figure 2.27 3-D views of model offices generated by energy plus (Korolija et al. 2013)

Susorova et al. (2013) studied the built-form under different climate conditions. Optimizing geometry parameters (window to wall ratio, window orientation, and width to depth ratio) can decrease building energy consumption in office buildings in all climate zones. The highest energy savings with fenestration geometry can be achieved in hot climates while energy savings in temperate and cold climates are marginal. The conclusions of Susorova et al. (2013) are summarised in Table 2.10.

Climate	Room geometry	Best performance	Lowest energy consumption
temperate and hot	shallow rooms	shallow rooms with medium-sized windows or large windows in deep room	north-orientated rooms with large windows/rooms with small windows facing south
cold	deep rooms	shallow rooms with small windows and medium-sized windows in deep rooms	south-orientated rooms with large windows

Table 2.10 Optimum building geomatry in different climates

2.5 Internal design conditions

Comfort in buildings

Buildings need to create a comfortable indoor environment for occupants and ensure that their health is not adversely affected. 'Comfort' has been defined as 'a condition of mind that expresses satisfaction with the environment (CIBSE 2015)'. The environmental factors of a building that affect occupants' comfort levels include the thermal, visual, and acoustic conditions, and indoor air quality.

There are individual differences in the perception of comfort, resulting in some dissatisfaction within the building population. Designers attempt to minimise dissatisfaction as much as possible. Since the relative importance of different aspects of comfort depends on the type of activities carried out, it is not practical to use a single index that quantifies the individual's responses to different environmental aspects. For example, people may prefer a warm environment in a restaurant, with moderate background noise and low levels of lighting; in a library, however, they may prefer the space to be cooler, with no background noise and high levels of lighting. Within office buildings, occupants carry out highly demanding mental tasks; therefore, to optimise worker performance, the office space is required to be thermally comfortable, quiet, and have a high lighting level.

2.5.1 Design temperature

A person's thermal comfort depends on both the thermal environment and personal factors. Thermal environment comprises air temperature, mean radiant temperature, relative air speed, and humidity. Personal factors include metabolic heat production and clothing.

Thermal comfort standards are in place to help building designers provide an indoor climate that building occupants will find thermally comfortable. The thermal condition of a building will not only determine the comfort level of occupants, but will also influence a building's energy consumption and its sustainability. With increasing pollution and climate change, a thermal standard should consider a building's environmental performance. It has been found that people are able to adapt to changing conditions. Setting thermal comfort standards that take into account people's ability to adapt may limit buildings' energy consumption (Nicol et al. 2002), (Nicol et al. 2017).

The adaptive approach to thermal comfort is based on the observation that people are active in relation to their environment. This means people tend to make themselves

comfortable, given time and the opportunity to do so by making adjustments to their clothing, activities, posture, and their thermal environment. For example, there is seasonal adaptation to outdoor temperatures – occupants may be happy with colder indoor temperatures in winter and higher indoor temperatures in summer. However, this correlation is found to be stronger in naturally ventilated buildings, while in mechanically cooled buildings, the outdoor temperature and comfort level is found to be decoupled. On a larger scale, the climate, culture, and design and operation of buildings influence the thermal environments that people find comfortable.

Given a type of climate, culture, and the design and operation of buildings, building service engineers aim to provide a thermal environment that is within the range customary for the particular type of accommodation. For a temperate climate such as that of London, CIBSE Guide A recommends for open plan, air-conditioned office buildings the operative temperature in winter to be 21-23°C and in summer 22-25°C. In a colder climate such as Norway, the indoor comfort temperature is generally found to be between 19-26°C (Brelvi 2013). In Japan, Takasu et al. (2017) found that in mix-mode offices, the comfort temperature is approximately 23.5-26.6°C. However, Takasu et al. (2017) also found that the optimum comfort temperature tends to increase and decrease at very low and high outdoor air temperatures, respectively.

2.5.2 Ventilation rate and infiltration

Ventilation is the process by which fresh air is provided to occupants and by which exhaled air, odour and pollutant are removed. In the latest Building Regulation in the UK, suggested minimum air supply rate per person is 10 l s⁻¹ for air quality in office buildings (HM Government 2015). Ventilation can be provided by mechanical, natural or mixed mode methods. Mechanical ventilation is applied by means of driving fans and a network of ducts. In large scale offices, mechanically ventilated supplied air is usually filtered and thermally conditioned.

Infiltration is defined as the uncontrollable air exchange between the inside and outside of a building through a wide range of air leakage paths in the building structure. The amount of the infiltration depends on the air-tightness of buildings and the wind. It was found that in real office buildings, the minimum infiltration rate found was 0.16 ach and the leakiest buildings had an infiltration rate of 1 ach (Korolija et al. 2013). 1 ach equates to all of the air within the internal volume of the building being replaced over a 1 hour period.

2.5.3 Relative humidity

Humidity affects the thermal comfort only when the temperature is high and the high humidity impedes the ease of evaporative cooling through sweating. The humidity of the indoor environment in the range 40-70% is acceptable but with the optimum being around 65%. Relative humidity needs taking consideration of latent heat gains. In hot and humid places such as Hong Kong, dehumidification is important and can be achieved by the HVAC system. Another side effect is condensation which can be mitigated by ensuring all surfaces are above the dew-point of the adjacent air. For heated-only buildings in the UK, the humidity can be below 40% which can cause dryness for office workers (CIBSE 2006).

2.5.4 Lighting level

The lighting level should be maintained at 300-500 lux. Most of the electrical energy used by a lamp is released as heat which is emitted by conduction, convection or radiation. When the light is switched on some of the heat is absorbed by the lamp, some of this heat is then transmitted to the building structure.

2.5.5 Occupancy density and internal heat gains

Internal heat gain features in energy demand calculations and is particularly significant in non-domestic buildings and especially in cooling seasons because there is a high usage of equipment such as computers. Internal heat gain is 'the sensible and latent heat emitted within an internal space from any source that is to be removed by air conditioning or ventilation, and/or results in an increase in the temperature and humidity within the space.' (CIBSE 2007). The main sources of internal gains within a building space are people, equipment and lighting. The amount of internal gains depends on the purpose of a building and its usage pattern. For office buildings, CIBSE Guide A has set standard value for sizing the plant as shown in Table 2.11. For example, in an office design a medium density i.e. 12m^2 per person would have 6.7 W/m^2 from occupants, 12 W/m^2 from lighting and 15 W/m^2 from equipment and hence has an overall internal gains of 33.7 W/m^2 . In a less dense office, for example 20m^2 per person the total internal gains would be 26 W/m^2 whereas the most dense office allowed would have 57 W/m^2 (4m^2 per person). These benchmarks are for standard working conditions. Lower levels of heat gain from light which is 8 W/m^2 can be achieved in new buildings based on fluorescent lamps. With LED lamps, these values can be reduced by up to 50%.

Density of occupation (person/m ²)	Sensible heat gain Wm ⁻²			Latent heat gain Wm ⁻²	
	People	Lighting	Equipment	People	Other
4	20	6-12	25	15	-
8	10	6-12	20	7.5	-
12	6.7	6-12	15	5	-
16	5	6-12	12	4	-
20	4	6-12	10	3	-

Table 2.11 Benchmark values for internal heat gains for offices (at 24°, 50%RH)

Azar and Menassa (2012) pointed out that the effects of occupancy parameters in energy simulation of office buildings are very significant. The authors analysed the sensitivity of the office building energy consumption with changes in buildings occupancy parameters. Thirty scenarios were modelled which include three building models in small, medium and large size under five climate conditions at two humidity levels (dry and moist). Nine occupancy related variables were tested: equipment and lighting use after working hours; cooling and heating set point during occupied hours and unoccupied hours; active HVAC system during after working hours; hot water consumption and building schedule which is the total number of occupied hours in a week. In large office buildings, it was found that the top three most influential parameters are building schedule, after-hour equipment use and the heating set point during occupied hours. This is the case under all five climate conditions. Another finding from the building survey is that large buildings usually have higher working hours. It varies between 60-80 hours per week whereas in small and medium office buildings it varies between 50-60 hours. Note that average notional contracted working hours is 36.25 hours per week. Specific job roles would require people working longer hours. For example, in financial services and legal service head offices, it is very common to have the building operate from 7am and till 8pm which means an over 12 hours period. Hence it is important to assess the sensitivity of the energy consumption with regard to different level of internal gains.

It can be seen that internal gains largely depend on the office layout or the purpose of the space. There can be variations in internal heat gains which are potentially not predictable which is found to be causing problems in the actual performance of buildings. The induced problem is called 'performance gap' which is explained in more detail in the next section.

2.6 Current problem of ‘performance gap’

Over recent years, it has been found that actual buildings do not always perform in the same way as predictions or initial designs. There are a few aspects of buildings’ performance gap such as air quality, comfort level and energy consumption. Among these aspects, the performance gap in energy which is a ‘mismatch between the predicted energy performance of buildings and actual measured energy performance’ is the most fundamental and problematic aspect. The actual energy consumption is often found to be much higher than the predicted value and the actual CO₂ emission levels are much higher than predicted. For example, in the UK non-domestic building sector, Menezes et al. (2012) found that the measured energy use can be as much as 2.5 times the predicted energy use. Figure 2.28 shows the predicted and actual energy consumption in schools, general offices and university campus. In the UK’s offices, the median of predicted CO₂ emissions is found to be around 43 kgCO₂/m²/yr but the actual emission median is as high as 68.9 kgCO₂/m²/yr (CarbonBuzz). In a study conducted in US, the actual energy use was found to be 10% higher than predicted and this value increases in proceeding years.

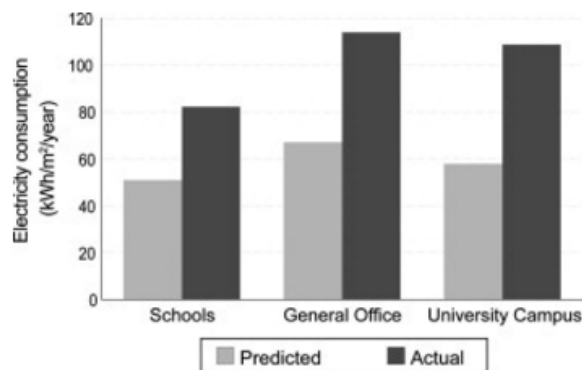


Figure 2.28 CarbonBuzz median electricity consumption per-sector – predicted vs. actual

Bridging this gap is important because of the increased pressure of the industry to address the challenges of environmental issues, rising energy prices and the expectation from the clients and general public to have new high performance buildings to meet increasing stringent energy efficiency targets (de Wilde et al. 2010). It is important to reduce this gap to when it is small enough, in order to be acceptable. This is particularly important when engineers want to deliver low carbon buildings/ high performance buildings which are robust towards change, have a good performance throughout their lifetime. The performance gap can only be bridged by a broad, coordinated approach that combines model validation and verification, improved data collection for predictions, better forecasting, and change of industry practice. (de Wilde

2014). Identifying and understanding the root causes of the energy performance gap is essential before any mitigation methods can be developed.

Causes of performance gap

One cause of the performance gap is that the energy consumption is overlooked in the design stage. AECOM carried out a desk study reporting the key issues and practical guidance in tackling the performance gap in order to meet the UK emission reduction target. As illustrated in Figure 2.29, the energy use within a building is typically broken down into 'regulated' energy use, and 'unregulated' energy use. The former represents all energy uses within a building that are accounted for within Building Regulation compliance software such as Simplified Building Energy Modelling (SBEM) or Dynamic Simulation Modelling (DSM). Such 'regulated' energy includes space heating, hot water, lighting, cooling and ventilation. In addition to 'regulated energy', there is 'unregulated' energy use which is energy consumption within an operational building, such as additional small power loads, external lights, and lifts. The 'unregulated energy' can often be overlooked in design. Additional energy may be consumed through inefficiencies of installed services due to ineffective management and/or poor commissioning. Non domestic buildings may have ancillary spaces such as reception, IT server room of which energy use would not normally have been included within in the energy model for that space. A change in predicted occupancy density or behavior, e.g. hours of use could also have a significant implications on the actual energy consumption of a building (AECOM 2012)

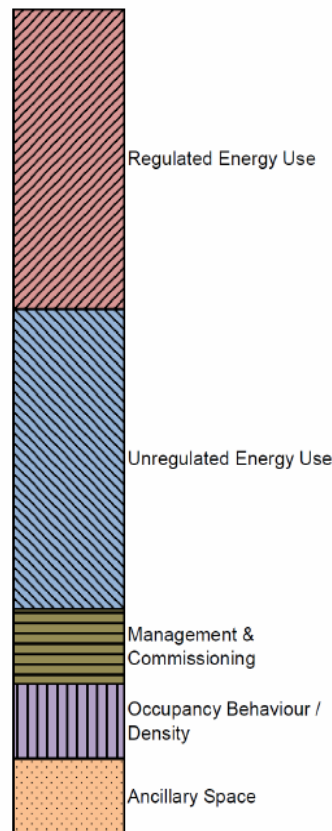


Figure 2.29 Classification of operational energy use (AECOM 2012)

A few authors, such as de Wilde (2014), Menezes et al. (2012) grouped the causes according to buildings' design stage, construction stage and operational stage. Some of the major reasons are briefly introduced here but the list is not exhaustive. During the design stage which is the process of predicting buildings' energy consumptions, errors can arise from design assumptions and the equations used by modelling tools (Menezes et al. 2012). The prediction model and designers often cannot fully predict the future use or function of the buildings because operational requirements and conditions might be subject to significant change. Inaccurate or wrong assumptions made at the beginning can cause inaccurate or wrong predictions of energy use. Sometimes the building design itself is inadequate through poor thermal concept. There can be wrong estimation of efficiency or size of HVAC and the schedules of HVAC and other office uses are underestimated in energy models. Raslan et al. (2009) found that there is variability in results produced by different simulation software which can be due to different modelling methods as well as the level of expertise of the program users. Logistically, problems can arise from miscommunications among clients and designers. Generally, there is a lack of feedback information from buildings under operation; one of the consequences can be wrong assumptions being made over and over again. During the construction process and handover to the client, problems

arise from construction quality, for example insufficient attention to both insulation and airtightness. Once the building is commissioned, lack of management and controls. All of these issues are interrelated, they are categorized under the broad headings shown in Figure 2.30.

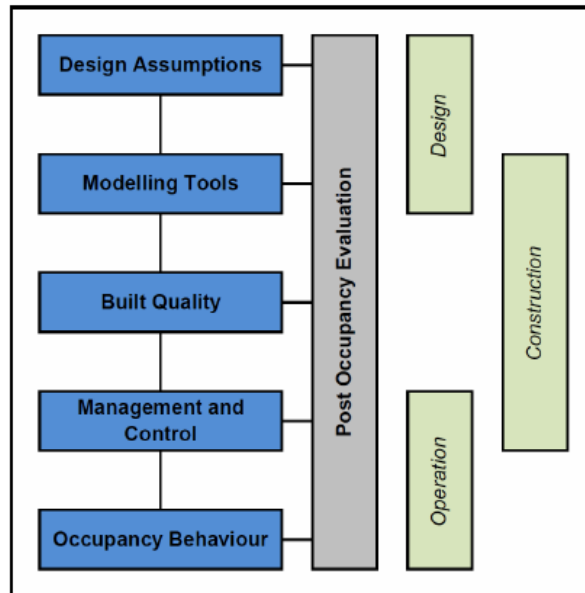


Figure 2.30 Categories of causes of performance gap and the role of POE, AECOM (2012)

Mitigation methods

Therefore, carefully planned office usage is a key to saving energy consumption. Basic strategies like monitoring, analysing energy consumption data, setting a person to be in charge of using the building properly, better management can help the building to improve its energy efficiency (Escrivá-Escrivá 2011). Dong et al. (2013) found that in commercial buildings, potential energy savings of 5-20% can be achieved through building control systems, which are Energy Management and Control Systems, occupancy sensors for lighting control, temperature control providing thermal comfort for occupants. An innovative building control approach which integrates local weather forecasting with occupant behavior detection can achieve 30% reduction in heating season and 17.8% in cooling season. The results also showed that cooling energy was more sensitive to changes in the occupancy level whilst the heating energy was not sensitive to the changes in occupancy level.

The report produced by AECOM (2012) has elaborated on the best practice and guidelines related to the headings in Figure 2.30 . For example, the client should provide good quality briefing information to the design team to help the design team to calculate the energy consumption of the building with greater accuracy, building

systems should be appropriately commissioned and the end users need to be trained in the operation of building services, etc

2.6.1 Variations in hours of work and internal heat gains

Occupancy behavior has been identified as the major cause of performance gap in energy consumptions. Accordingly, the Task group has identified the key aspects of closing the gaps which are: improving prediction and better analysing real operational energy use. It is an area that attracted much attention and the following studies used real data to further understand the influence of occupancy behaviours.

In the report by AECOM (2012), uncertainty in occupancy behavior is a large contributor to extra energy consumption. It was found that in air conditioned offices, the more energy is used during non-working hours (56%) than during working hours (44%) and the largest consumers of energy were air conditioning systems, followed by equipment left on unnecessarily at the end of day and lighting. It also highlighted the value of using Post occupancy evaluation (POE) to understanding performance gap. POE provides mechanisms to support collection of actual building energy use data, reporting and associated feedback within the construction industry.

Menezes et al. (2012) demonstrated how Post-Occupancy Evaluation (POE), which is achieved through systematic data collection, can be used to produce more accurate energy performance models using a case study of a high density office building in central London. The study focused on collecting actual electricity consumptions for lighting, small power and catering in case study buildings as their real usage do not matches with the prediction models. Walk through inspections show that there are underestimations of small powers, employees leave computers on overnight. It has also been found that offices are now run for longer working hours. The study recommends feeding the monitoring results into energy models to provide better energy consumption prediction. Adjusting the occupancy hours seems to have the highest impact towards achieving an increasingly accurate prediction. The study did not investigate their influences on thermal loads but pointed out that better prediction of internal load would improve the prediction of cooling and heating demand in a building.

Korjenic et al. (2012) carried out a case study in validation and evaluation of total energy use in an office building. Detailed energy use for the tested office building was recorded for a year and compared with the results from the dynamic simulation program. It was found that when the input is close to real, the simulation program can give a reasonably close prediction. The variation caused by not using the actual climate

data is also small. The work recommended testing a range of different potential building use and equipment scenarios during the design phase.

Sun (2014) attempted to improve the prediction capability of building energy models by quantifying uncertainty that may occur over the future or event of interest. The work provides theories and models that enable probabilistic prediction over future energy consumption, forming the basis of risk assessment in decision making. Actual hourly sub-metered energy consumption data collected from 6 case study buildings was used to verify the method, it was shown that it is possible to reduce the mean absolute error in annual energy consumption by quantifying and account uncertainties during design stage. One application is that it can provide more realistic heating and cooling load prediction and improve the situation of commonly observed oversizing HVAC plant which is costly. The common approach of ensuring a system meets the required level of performance is by applying a safety factor but a new design method based on dynamic simulation with inclusion of quantified uncertainties has the potential to give more sensible system sizing. The sensitivity of six groups of parameters which are weather, microclimate, building envelope, material properties and operations are assessed in the study. Among these parameters, occupant density, effective leakage area and weather are found to be the most influential. The study showed that the occupancy density is particularly important, with a sensitivity index (SI) of 41.8% in cooling peak load.

2.6.2 Implication of performance gap on facade design

There is plenty of evidence showing that the uncertainty in occupancy behavior is the main cause of performance gap. Most of the current research effort has been put into how to better predict the occupancy behaviour and therefore the energy consumption at the design stage. In large scale office buildings, it has been found that there is a tendency of over usage of buildings and the actual occupancy hours are longer than assumptions. The studies also suggested that different equipment usage should be considered at the modelling stage. Knowing that both façade's thermal performance and variations in occupancy level have large impact on buildings' energy performance, it has become obvious that it is important to assess whether the change in building usage would change the optimum façade design. However, none of the studies investigated the impact of variation of occupancy level on facade selections. Given the significance of the influence of variation in occupancy behaviour, façade designs need to be 'occupant proof' in order to create truly low energy office buildings.

2.7 Climate change

Buildings normally have a lifespan of 50-100 years during which the climate may vary. In the UK, it is predicted that there is 50% probability that the temperature will increase by 2.4 °C to 4.8 °C on the warmest day in summer depending on the location (de Wilde and Tian 2010). Researchers have been investigating the influence of future climate change on building energy performance. Some studies have suggested that the annual heating demand and cooling demand of buildings would change as a result of climate change. The actual amount of change depends on climate zone (Wan et al. 2011), building types and other parameters such as internal gains. For example, in Switzerland, a typical multistorey heavyweight building with different levels of insulation and internal heat gains was investigated assuming a temperature rise of 4.4°C in year 2050-2100. The results showed that the cooling energy demand is expected to increase over 200% and the heating energy demand to reduce by more than 50% (Frank 2005). This is also true of many other countries in Europe and also China.

However, there are different opinions regarding the effect of climate change on the energy performance of office buildings in the UK. For example, in the UK, de Wilde and Tian (2010) suggested climate change would bring a slight decrease in annual carbon emissions with no other significant impact based on a three-storey office building model. However, another study based on a mixed-used building model showed that the amount of the GHG emission caused by space cooling can increase by 26%-70% depending on the future climate change situation (Williams et al. 2012). Therefore, there is a need to further study the potential effect of climate change on the office building energy usage.

Furthermore, the cities' micro climate is changing. The heat island effect is a rise in diurnal dry-bulb temperature due to the concentration of population, infrastructure in cities. In cold climates, the urban heat island effect would have a positive impact and result in energy reduction. However, in tropical climate, buildings may experience an increase of 20% in overall energy use (Crawley 2008).

Therefore, with proven evidences showing that the ambient temperature is likely going to rise in the coming years and it will have an impact on the heating and cooling requirement of buildings, it is important to investigate the influence of climate change on facade selection.

2.7.1 Implications of climate changes on facade design

Ideally, the design of newly built buildings should have an optimized design taking into account the effect of future climate change. How will climate change impact on air-conditioned office buildings? What are the implications on office building facade design? The literature on these aspects is limited and it is not clear how best to account for the effects of climate change on the development of zero carbon non-domestic buildings.

2.8 Discussion of current building regulations

The fact that a performance gap exists means the current building regulations in the UK might not be sufficient to guide designers to use optimum facades that are resilient to both this factor and climate change. The future development of the building regulations are of high interest for the industry.

2.8.1 Current mechanism of achieving compliance

There is a legal requirement to lower CO₂ emissions from buildings. For example, the European Performance of Buildings Directive (EPBD) which came into force in 2003 promotes the improvement of energy performance of buildings within the EU through cost-effective measures (Ekins and Lees 2008). Many countries from Europe, including the UK, are bound by the EPBD and their building regulations have to comply with the EPBD. There are four main requirements of EPBD which are as follows:

- 1) Establish a calculation methodology for the overall energy performance of buildings, considering at least the following influencing factors: thermal characteristics and air-tightness of the building envelope and internal partitions; heating installation and hot water supply, including their insulation characteristics; air conditioning and built-in lighting installation; ventilation and natural ventilation, position and orientation of buildings including outdoor climate; passive solar systems and solar protection, and indoor conditions.
- 2) Set minimum energy performance requirements for new buildings and for large existing buildings when refurbishment takes place;
- 3) When buildings are constructed, sold or rented out, an energy performance certificate must be produced;
- 4) Inspections of boilers and air-conditioning must be included in the regulations.(Anderson 2006)

The EPBD also requires Member States to ensure that by the end of 2020 all buildings are nearly zero-energy buildings (NZEB), and after 2018, new buildings occupied and owned by public authorities are NZEB (Erhorn-Kluttig 2015).

As a Member State of the European Union, the UK has developed its Building Regulations and relevant tools in order to comply with the EPBD. Part 6 of the UK Building Regulations sets energy efficiency requirements for buildings. These requirements focus on regulating the overall CO₂ emission rate.

Approved Document L2A: Conservation of fuel and power in new buildings other than dwellings provides further practical guidance on how to achieve the energy efficiency requirements of the Building Regulations for new non-dwelling buildings in England (DCLG 2016). This includes limiting the maximum U-values for building envelopes and limiting the effects of solar gains during summer via the 'g-value' of glass. The document states that the calculated CO₂ emission rate for the new building, the Building Emission Rate (BER) must not exceed than the Target Emission Rate (TER). The BER and TER are calculated by the National Calculation Methodology.

The National Calculation Methodology (NCM) developed by the Department for Communities and Local Government (DCLG) defines the procedure for calculating the annual energy use and carbon dioxide emissions for a proposed building (BER) as well as the energy use of a comparable 'notional' building (TER). The Notional Building substitutes building fabric, glazing type, air tightness and HVAC and lighting plant by specified standard items and keeps the rest of the parameters, for instance, geometry, orientation, usage, operating pattern, weather data the same as the evaluated building. 'Notional building' models are specified according to the 2010 NCM Modelling Guide (DCLG 2010). The NCM contains both the underlying method and the standard data sets needed in the process. Therefore, designers have the freedom to select an appropriate facade for buildings to outperform the notional buildings in terms of CO₂ emissions.

The National Calculation Method allows the actual calculation to be carried out using Simplified Building Energy Model (SBEM) for non-residential buildings developed by the Building Research Establishment for the Department of Communities and Local Government. SBEM can analyze a new non-domestic building's energy consumption and determines its CO₂ emission rate in compliance with Part L of the Building Regulations. It can also be used to generate Energy Performance Certificates. Users have to specify details of the fabric construction, building services for heating, air conditioning and ventilation, and other factors mentioned in the EPBD requirements as

well as the use of low and zero carbon technologies (LZCT) such as solar panels and photovoltaics. Other approved simulation software from various developers can also be used instead of SBEM, especially those with more innovative features which may not be modelled adequately in SBEM. The common simulation software used in the UK include IES VE (IES 2015) and EDSL TAS (EDSL 2012) which will be discussed in more detail in chapter 3.

2.8.2 Future development of building regulations

As previously discussed that the UK has set out policies which are designed to regulate new buildings' CO₂ emission rates and also gives some practical guidance on how to conserve energy. Facades play an important position in Building Regulations. The main focus is to improve the thermal performance of facades by limiting the overall U-value and controlling solar heat gain through windows.

The rising concern for climate change has driven the shift in Building Regulations from feature-based towards overall performance based requirements (Crawley et al. 1999, Meacham et al. 2005). For example, in the UK, the maximum allowable U-values of building envelope components were significantly reduced between 1995 and 2002. They have remained constant since 2002 and indeed the most recent edition of the Building Regulation which was published in 2013 still retains the same requirements.

In 2011, the UK Department for Communities and Local Government commissioned an AECOM-led consortium to further develop guidelines to help achieve the zero carbon building standards. However, it suggested no further reduction in U-values in order achieve better energy efficiency at least up to 2019 since the potential beneficial impact was found to be very small – only 1-2% on CO₂ emission reduction. The report pointed out that improving window property such as its g-value, which would result in lowering solar heat gains, might have a larger beneficial impact (AECOM 2011). Table 2.12 shows the historical maximum allowable U-value and the projected maximum U-value for 2019.

Year	External			
	Wall	Roof	Floor	Windows/curtain wall
1995	0.45	0.25	0.45	3.3
2002	0.35	0.16-0.25	0.25	2-2.2
2006	0.35	0.25	0.25	2.2
2010 (DCLG 2010)	0.35	0.25		2.2
2013(DCLG 2013)	0.35	0.25	0.25	2.2
2019(AECOM 2011)	0.35	0.25	0.25	2.2

Table 2.12 Historic maximum allowable u-values (W/m²k) for new non-residential buildings in england and wales

However, because the U-value of the external envelope is assumed as 1.6 W/m²K in notional buildings and the maximum allowable U-value is 2.2 W/m², it seems to encourage the use of low U-value facades. Therefore, in practice, facades with U-values well below 2.2 W/m²K are used.

Furthermore, the UK-GBC Zero Carbon Non Domestic Task Group suggested the future changes to Building Regulations should be (1) Target Fabric Energy Efficiency (TFEE) rate' will be introduced to reinforce the importance of elemental efficiency (2) embodied carbon needs to be better measured and reduced, (3) further develop SBEM to generate more accurate predictions of energy use in building by considering, for example, different occupancy scenarios which requires feedback from operators of non-domestic buildings, (4) in the longer term, disclosure of operational energy usage and having operational energy certificate should be mandatory, (5) investigate an alternative, quicker route to show compliance for simple buildings (UK-GBC 2014).

Following the general election in 2015 the UK Government published 'The Productivity Plan' in which the 2016 zero carbon homes and the 2019 zero carbon non-domestic buildings targets were dropped (CIBSE 2015). Nevertheless, low carbon or nearly zero energy buildings are still of interest in the UK, US and the rest of the world given the imminent climate change problem. Hence, study of the basic energy demand of office buildings through improving fabric efficiency is still key to providing a knowledge base to reach the low carbon low energy building goal.

2.9 Summary and conclusions

This chapter introduces the challenges of designing low-energy and low-carbon offices globally. High performance curtain walls (low U and low g-value) have been developed to help reduce energy and CO₂ emissions from office buildings. It then reviews the current developments of high-performance facades and existing studies related to the energy performance of high-performance facades. Low U-value facades should stop heat from escaping during cold weather conditions but also prevent heat from entering buildings during warmer periods. However, the studies that have been carried on office buildings in both cold and hot climates appear to provide conflicting results. The different opinions on the benefit of low-U value façade found in the existing studies might be caused by the fact that different assumptions and modelling methods have been used. It can be concluded that there is a clear gap in understanding the impact of high performance facade, more specifically, low U-value facade in low carbon office design, in the UK as well as in the rest of the world.

Furthermore, it has been found that there is a significant ‘performance gap’, which is the difference found between the building’s predicted and actual energy consumption, in offices. The largest cause is inaccurate prediction of internal gains, which include over-usage of buildings and variations in internal heat gains. Climate change is another important element to consider during the facade design stage. Both factors appear to have a great influence on the energy performance of buildings, however, the literature on their influence on facade design is very little. Therefore it is important to assess their effect on optimum facade design, aiming for ‘future proof’ buildings.

The fact that a performance gap exists means the current building regulations in the UK might not be sufficient to guide designers to select optimum facades that are resilient to variations in building usage, the largest contributor to the performance gap. Furthermore, whether the optimum façade design selected at the early design stage is robust to change in climate needs to be investigated.

Therefore, the following research aims are formed

- 1) To investigate the influence of low U and g-value facade on heating/cooling demand and CO₂ emissions in office buildings in four climatic zones, i.e. cold, cool, sub-tropical and hot.
- 2) To assess the impact of the performance gap on facade selection under the above-mentioned climatic conditions

- 3) To investigate the influence of climate change on facade selection under these four climatic conditions.
- 4) To investigate the influence of low U and g-value facades on CO₂ emissions of office buildings under these four climatic conditions.
- 5) Based on the results of these investigations, to elucidate the potential of low U and g-value facades, to achieve the low carbon emissions goal in office buildings.
- 6) To assess the effectiveness of building regulations in the UK, and to propose appropriate improvements.

The existing studies have used different assumptions and modelling methods and have reached conflicting conclusions. In order to gain a deeper understanding of these different opinions and answer the proposed research questions, the next chapter develops a fit for purpose and robust method and a test programme. It begins by giving a review of calculation methods of heating and cooling energy demands of buildings.

CHAPTER 3 DEVELOPMENT OF METHODOLOGY

Introduction

As discussed in Chapter 2, energy consumption and CO₂ emissions from office buildings are global problems which need to be tackled urgently. The use of high performance facades in office buildings is one possible solution to these problems. However, their benefits remain unclear with some advocating that they will reduce energy demand and hence carbon emissions in both hot and cold climate whereas others appear less certain. There are also uncertainties due to changes in building usage and climate change, which might affect the optimum U and g-values of facades. Hence, it is important to ascertain the energy saving potential and CO₂ emissions reduction potential of high performance facades under different external climate conditions and internal design conditions.

An appropriate method of assessment is needed to assess and compare energy performance of facades under these conditions. In the literature, there are a number of ways of comparing energy performance of facade systems. Some researchers have used life cycle analysis to compare energy performance of facades as shown in Chapter 2. However, whereas embodied energy is more straightforward to predict and control, it is considerably more complicated to predict operating energy of buildings. Hence, embodied energy is outside the scope of this project.

As for predicting operating energy consumption from office buildings, there are a large number of case studies using different methods and assumptions. Hence, the aim of the work reported in this chapter is principally to develop a consistent and fit for purpose model for assessing energy performance of office buildings utilizing different facade types.

We begin by providing an overview of the process of designing a heating and cooling system and calculating building energy consumption in a mechanically cooled office building.

3.1 Building energy demand

This section describes how facades influence energy usage in buildings and the reason why energy demand can be used as a performance indicator for this element of structure.

3.1.1 Overview of building energy design process

The implementation of the European Performance of Building Directive (EPBD) through a National Calculation Methodology places energy efficiency and CO₂ emissions at the core of the design process. Figure 3.1, adapted from CIBSE Guide A 2006 (CIBSE 2006), shows the process involved in calculating heating and cooling loads, and heating plant capacity for mechanically heated and cooled buildings.

Design calculation is a sequential iterative process which is repeated at conceptual, detailed proposal (scheme) and final proposal (detail) design stages. While empirical rules of thumb may be appropriate at the concept stage, later design stages will usually require better accuracy and quality, less uncertainty, a clear understanding of the sensitivity to assumptions and reduced risk (CIBSE 2015).

The first stage of the design calculation process involves setting up a project quality plan. Its aim is to select appropriate calculation methods, which might involve carrying out simple hand calculations or using sophisticated software and ensuring that the stated methods are fit for the purpose, avoiding or reducing errors arising, for example, human error in entering data, provide an audit trail of calculations for future scrutiny and to implement best practice.

The second stage is to select design parameters which are appropriate to the location of the site, internal design conditions, appropriate heating criteria, external design conditions, infiltration and ventilation requirements, internal gains and patterns of use, building fabric properties and building geometry.

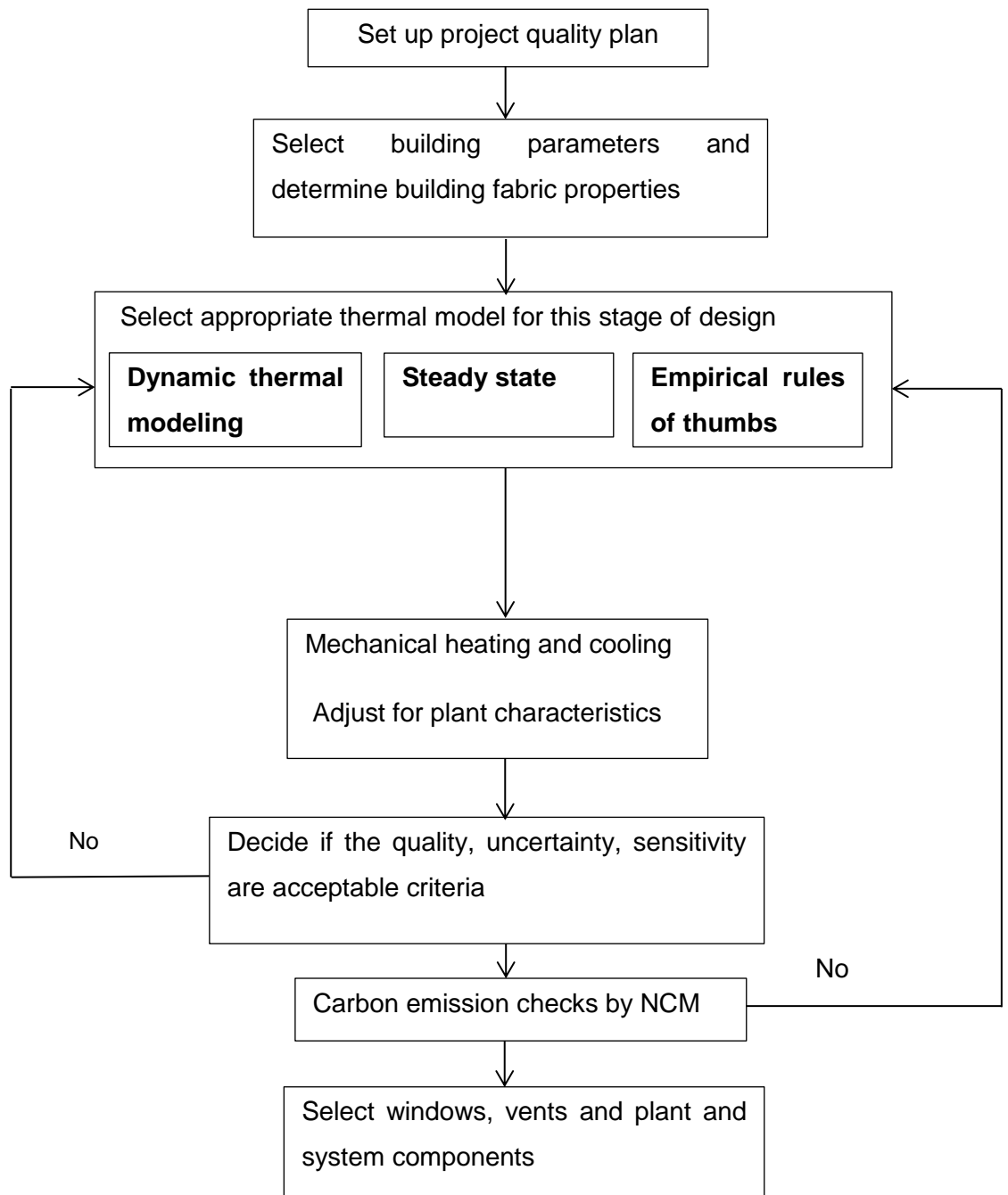


Figure 3.1 Thermal modelling and plant sizing flow diagram (adapted from CIBSE Guide A 2006)

There are a few types of thermal models available. They include empirical design guides, rules of thumb, steady-state methods and dynamic thermal modelling. Whereas design guides and steady-state methods are more transparent and have value in educating users about the process involved, dynamic thermal modelling is thought to be the most reliable way of load calculation.

Once the heating and cooling load/demand has been determined, a heating and air conditioning system can be designed to meet this demand. In order to size the plant, designers are primarily interested in peak temperatures which occur during extreme weather conditions, i.e. heat waves in summer or cold spells in winter. Peak temperatures are used to assess the heating and cooling capacity of the plant required. Hand calculations allow a quick assessment of peak loads. Examination of annual performance has also become increasingly important because of climate change and resource depletion (Kreider et al. 1994).

The use of computer aided design techniques has increased in popularity because they can carry out dynamic simulations for energy demand calculation as well as carrying out subsequent design steps of estimating energy consumption and checking buildings against the National Calculation Methodology.

These software tools have great capabilities, they can perform thermal modelling and predict air movement within a building. Apart from space conditioning, the energy used for lighting, domestic hot water and mechanical ventilation also need to be predicted and accounted for when checking buildings' acceptable CO₂ emissions using the National Calculation Method (NCM). Simulation software cannot only be used for checking against NCM but more importantly to develop more energy efficient building designs.

The relationship between energy demand, energy consumption and CO₂ emissions is shown in Figure 3.2.

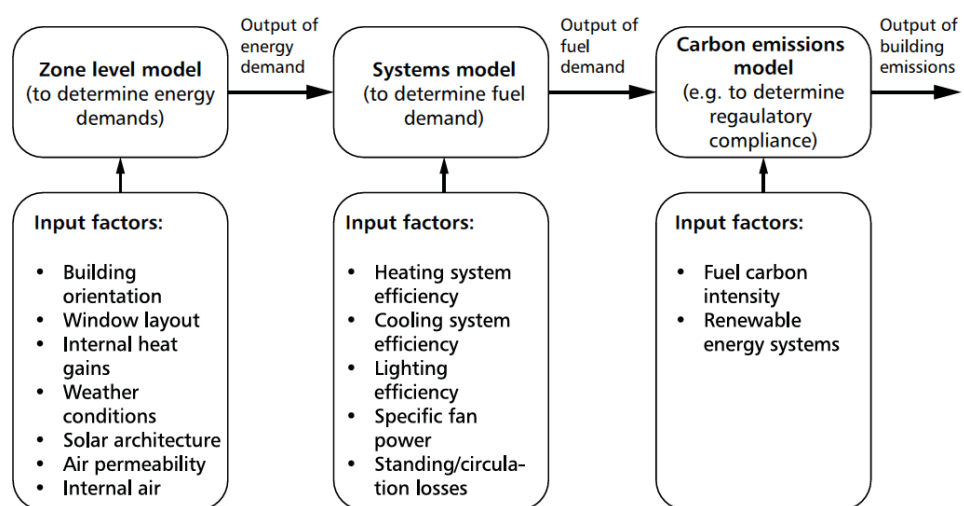


Figure 3.2 Energy model input and output relationships (CIBSE 2015)

Annual energy consumption for space conditioning is the time integral of the instantaneous consumption over the heating and cooling season; the instantaneous consumption is the instantaneous load divided by the efficiency of the heating or cooling equipment.

However, there are concerns raised regarding understanding the results of the dynamic thermal modelling. The large and detailed amount of data generated from these software need a good reviewing system which is also a part of the quality plan. A sensible approach to post-processing and interpreting data can help designers to generate a better understanding of the results and influence on design decisions. It is a great challenge for a practitioner to describe complex phenomena and deliver clear and concise results as a part of clear and concise message to people who are not familiar with the techniques.

3.2 Heat balance equation

Before going into details of currently available steady-state calculation methods and dynamic simulation programs, heat balance principle and basic load calculation equations which are the foundation of both steady-state methods and dynamic simulation programs are briefly reviewed here.

Figure 3.3 shows the principal factors influencing the thermal behaviour of an enclosed space. A factor not shown is the thermal mass of the building. This is 'the heat absorbed by the mass of the building which does not contribute to the loads until several hours later'. The effect of heat storage/thermal mass is more significant in peak cooling load calculation but less so in peak heating load and annual energy consumption calculations (Kreider and Rabl 1994).

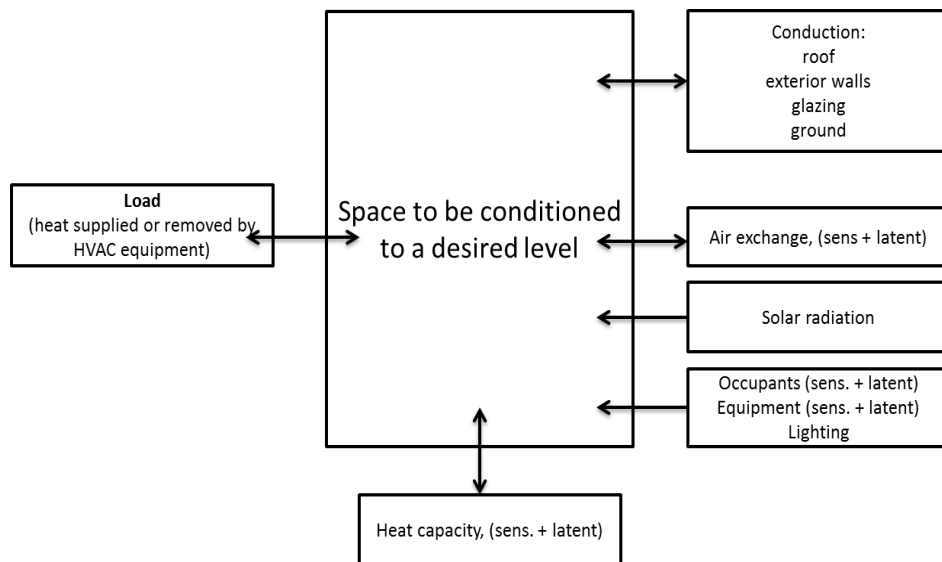


Figure 3.3 Heat balance diagram (Kreider and Rabl 1994)

3.2.1 Load calculations

Loads are sensible (affecting air temperature) or latent (affecting relative humidity) or a combination of sensible and latent.

Total sensible load

Q_{cond} , conduction: the total conductive heat flow through building envelope other than ground. In most buildings, the envelope consists of a large number of different parts. The amount of detail to be taken into account depends on the desired level of accuracy. The three main elements of a building envelope are glazing, opaque walls, and roof.

Q_{air} , air exchange: heat gain/loss due to air exchange as a result of infiltration and/or ventilation,

Q_{floor} , conduction through floor: it is normally not proportional to ΔT . In traditional construction, the heat gain from this source is small and hence is often neglected. However, this factor might become significant in super-insulated buildings.

Q_{sol} , solar radiation: heat gain from solar radiation

Q_{int} , internal gains: heat gains from occupants, equipment and lighting

Q_{stor} , thermal storage: heat storage capacity of construction materials. It is included in the dynamic analysis but neglected in steady-state analysis.

Sensible load is defined as

$$Q = Q_{cond} + Q_{air} + Q_{floor} + Q_{int} + Q_{sol} \pm Q_{stor}$$

EQUATION 5

In which,

$$Q_{cond} = \Delta T \sum_k U_k A_k$$

$$Q_{air} = \rho c_p V \Delta T = \frac{1}{3} NV \Delta T$$

$$Q_{floor}$$

$$Q_{sol} = g A_w S_o$$

$$Q_{int} = Q_{lit} + Q_{equ} + Q_{occ}$$

And,

$\Delta T = T_o - T_i$ (exterior temperature – interior temperature)
 U_k = thermal conductance of external envelope element k
 A_k = the area of external envelope element k (m^2)
 g = g-value of the glazing
 A_w = area of the window (m^2)
 V = volume of the room (m^3)
 S_o = incident solar irradiance on the window (W/m^2)

Latent load

Total latent heat gains are mainly due to air exchange, equipment, and occupants and can be calculated in accordance with Equation 6.

$$Q_{lat} = Q_{lat, air} + Q_{lat, occ} + Q_{lat, equ}$$

Equation 6

If Q_{lat} is positive, a cooling load is required whereas if Q_{lat} is negative, a heating load is required.

The parameters involved in the load calculations are summarised in Table 3.1.

Location of the site		
Internal design conditions	Heating set-point humidity	
External design conditions	Temperature: dry bulb and wet bulb Solar data: solar irradiation, sol-air temperature Wind speed and direction	
Infiltration	Air-tightness	
Ventilation types and requirements	Natural ventilation vs mechanical ventilation Ventilation requirements	
Internal gains and patterns of use	Equipment Light Occupant Occupancy hours	
Building fabric properties	Principal fundamental properties	Principal derived properties
	Density Specific heat capacity Thermal conductivity Thermal resistance Vapour resistivity Absorptivity Emissivity Solar transmittance Solar absorptance Solar reflectance Light transmittance	Thermal transmittance (u-value) Thermal admittance (Y-values) Decrement factor Surface factor Solar gain factor for transparent materials
Building geometry	Layout, window to wall ratio	

Table 3.1 Summary of building parameters related to thermal performance

3.3 A review of steady-state methods

Steady-state methods are based on simplified mathematical equations and mostly can be carried out using Excel spreadsheets. Simplified modelling involves the use a virtual physical model and the application of calculations that involve using average values of the internal and external factors that affect the energy performance of a building. This can reduce the amount of input data to manageable levels, in reality the magnitudes of each of these vary independently of each other over time. In simplified calculation methods, certain assumptions are made to the underlying model. Some of the energy that interacts in a dynamic fashion may either be approximated or entirely omitted (Raslan 2010).

There are a number of steady-state calculation approaches that have been used to assess the thermal performance of buildings, for example, the Degree day method (CIBSE 2006), and Overall Thermal Transmission Value Method which have been developed to assess the energy performance of buildings and facades. Some researchers also used simple mathematical relationships to investigate the relationships between major parameters. This section reviews the principles of some of the steady-state methods that have been found in the literature in order to determine their suitability for use in this study.

3.3.2 Degree-days method

One of the main uses of the Degree-day method is to estimate energy consumption and carbon dioxide emissions due to space heating and cooling for new build and major refurbishment. The Degree-Days method can provide a simple, manual estimation of annual loads, subsequently fuel consumption and CO₂ emissions (CIBSE 2006). Degree-days are the summation of temperature differences between outdoor air temperatures and a base temperature over a specified time period. They capture both extremity and duration of outdoor temperatures. The determination of the base temperature relates to the energy balance of the building. The base temperature is a balance point temperature, i.e. the outdoor temperature at which the heating or cooling system do not need to run in order to maintain comfort conditions. All gains such as equipment and solar gains are considered when determining this base temperature. In heating seasons, heat gains help to reduce the heating demand. Heat gains increase the cooling load in cooling seasons. The effect of thermal mass of buildings can also be included in this method. It is being used globally, heating degree-days and cooling degree-days data are available for countries around the world. The data can capture the severity of a climate. For example, as shown in Table 3.2, Abu Dubai has a high number of cooling degree-days (CDD) and a small number of heating degree-days (HDD) which suggest that cooling is dominant. The UK has a high HDD but lower CDD and this suggest that heating is dominant.

Station Name	Latitude	Longitude	Elevation (m)	HDD	CDD
LON HEATHROW	51.48N	0.45W	25	4790	169
SHANGHAI HQ	31.17N	121.43E	7	3032	2068
HK OBSERVATION	22.30N	113.92E	8	327	4055
ABU DUBAI	24.43N	54.47E	3	28	6262

Table 3.2 Examples of heat degree days and cooling degree days of four places (ASHRAE 2009)

The degree day method can be used to estimate annual energy consumption of buildings and it provides transparency and repeatability. However, it is still a relatively long method and cannot provide a rapid assessment of the energy performance of facades therefore it is not used in this study.

3.3.1 Overall Thermal Transmission Value Method

The Overall Thermal Transmission Value (OTTV) method gives a measure of heat transfer from the external environment to indoor environment through the external envelope of a building. It considers three components of heat gain/loss: conduction through the opaque wall (Q_w), conduction through fenestration (Q_f) and solar heat gain through the fenestration (Q_s). The method assumes solar heat gain is the dominant heat gain component in buildings. The actual proportion of each component varies in different situations depending on the building design and prevailing climate condition. It is an index of the overall thermal performance of a building envelope. The usual practice is to have two separate OTTV values for roofs and external walls. The smaller the OTTV value, the smaller the energy required. Equation 7 shows the OTTV for external walls.

$$OTTV_i = (Q_w + Q_f + Q_s) / A_i$$

$$= [(A_w \times U_w \times TD_{eq}) + (A_f \times U_f \times DT) + (A_f \times SC \times SF)] / A_i$$

Equation 7

$$OTTV_i = (1 - WWR) \times TD_{eq} \times U_w + WWR \times DT \times U_f + WWR \times SC \times SF$$

OTTV = overall thermal transmission value

A_i = the gross area of the walls = $A_f + A_w$

A_f = area of fenestration

A_w = area of opaque wall

TD_{eq} = equivalent temperature difference

DT = temperature difference between exterior and interior design conditions

U_w = U-value of walls

U_f = U-value of fenestration

SC = shading coefficient = $SHGC/0.87$

SF = solar factor = $0.87 \times$ incident solar intensity

WWR = 'window to wall' ratio which is the ratio of window area to gross wall area = A_w/A_g

$TD_{eq} = DT + [\alpha \times R_{so} \times \text{avg}(I_t)]$

α = absorption coefficient

R_{so}

I_t = the solar intensity falling on the surface (W/m^2)

Equivalent temperature difference, TD_{eq} , considers both the conduction heat gain due to the temperature difference between indoor and the outdoor environment and the effect of solar radiation on opaque surfaces. The effect of heat gain due to radiation on opaque surface is accounted for by considering wall material properties, the absorption coefficient of the opaque wall surface and the outside surface resistance. Further details of this method can be found in (Yang et al. 2008). The assumption is that the building is completely enclosed.

The method was first introduced in the energy conservation standards of ASHRAE standard in 1975 in America as a thermal performance index for the envelope of air-conditioned buildings. It was used for 14 years but not featured in the standard since 1989 in the US. However it is still used in a number of Asian countries like Hong Kong who launched OTTV in its Building Regulation in 1995. The Malaysia Building code require that the OTTV must not be greater than $50W/m^2$ for non-residential buildings with air-conditioned areas larger than $4,000m^2$.

Because it only considers the heat transfer through the building envelope, it seems to be a good way of comparing the energy efficiency of different facade systems, it remains as a simple way of assessing the thermal performance of building envelope and is still used for research purposes and in Asia places such as Hong Kong (Yang et al. 2008) and Thailand (Chirarattananon et al. 2004). However, due to the simplicity of the method, it has many limitations, for example, it does not consider internal heat gains which are important in office buildings. It remains an inadequate measure of the envelope performance and detailed computer simulations are preferred. Yik et al. (2005) in Hong Kong questioned the effectiveness of OTTV in building energy regulatory due to its simplicity.

The method is not used in this study because it does not consider the effect of internal heat gains which are important in buildings. However, the features of this method such as using seasonal average values which makes it quick to perform, the method based on the heat balance equation which is simple and clear should be incorporated while developing a fit for purpose method for this study.

3.3.3 Simple mathematical relationships

g/U against $\Delta\theta/I$ to assess the energy performance of glazing

Manz et al. (2012) developed a simple method to analyze energy flow in glazed facades and used it to assess the performance of four types of glazing (Table 3.3) in eight European cities. Parameters assessed include glazing quality, facade orientation and climate conditions. Glazing quality was represented by the ratio of the total solar energy transmittance (g) to thermal transmittance (U). Climate characteristics are represented by the ratio of the interior-exterior temperature difference ($\Delta\theta$) to the solar irradiance (I). Monthly mean values of interior-exterior temperature difference and solar irradiance were used. The results for London, one of the locations investigated is shown in Figure 3.4. Here, α is the gain-to-loss ratio = $g / U \Delta\theta$. When $\alpha > 1$, there is a net heat gain through the glazing, whereas $\alpha < 1$ when there is net heat loss through the glazing. The trends found in the study are not surprising: triple glazing performs the best, it guarantees net heat gains in South, East and West orientations whereas traditional single and double glazing lead to heat loss in most cases. Charts have been produced to present condensed information of energy performance of glazing. The author thinks this simplified approach is straightforward and may be valuable for educational purposes.

Glazing type	U(W/m ² K)	G	g/U	Constructions details
A (3-IGU)	0.4	0.47	1.175	modern insulating glazing unit with three panes, both cavities filled with krypton and two low emissivity coatings
B (2-IGU)	1	0.6	0.6	modern insulating glazing unit with two panes, cavity filled with argon and one low-e coating
C (Double)	2.9	0.77	0.266	double glazing with no coatings and gas fill
D (Single)	5.9	0.87	0.147	single glazing with no coatings

Table 3.3 Construction of four types of glazing investigated Manz et al. (2012)

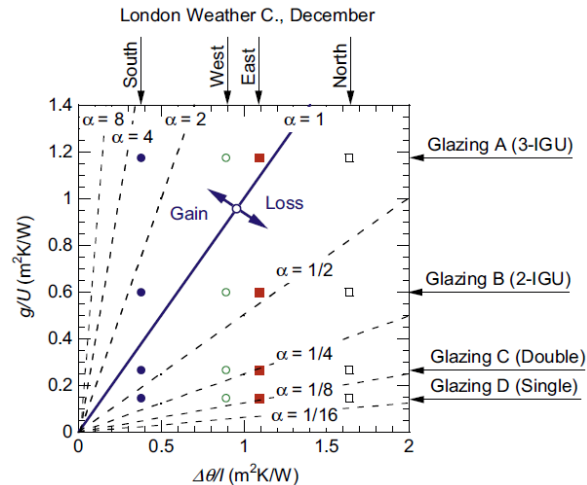


Figure 3.4 Gain-to-loss ratios of four glazing type under London climate condition

Although the display of the results is straightforward and allows the focus being on the four most important parameters influencing energy performance, drawbacks of this study are that only December is investigated. The method itself is crude and the trend lines have not been verified with results from more sophisticated models. Furthermore, the results might change if high internal gains are taken into account.

3.3.4 The value of steady-state methods

The general feeling about steady state methods is that they are too simple. They are incapable of accurately modelling energy consumption because of their limited ability in representing the complex processes occurring in buildings. For example, the overall thermal transmission value method allows designers to focus on the envelope. The OTTV method highlights the parameters most relevant to designers. However; the heat gains/losses due to occupancy/equipment and ventilation, which are important factors are not considered. The method is quicker and results are easier to interpret. Simple mathematical relationships can highlight the correlation between important parameters such as temperature, solar intensity, U and g values. It is useful to produce a graph which condenses information for a particular location. It is useful to show climate characteristics so designers can have a direct view of how climate condition of a location and make easy comparison of different climate conditions. However, some authors argue that steady state methods have indicative, educational values. They are simpler to use and the results obtained are almost invariably on the conservative side, useful for checking against gross errors (Muncey 1979).

In UK engineering practice, manual calculations are often used to determine peak loads for buildings in order to size the HVAC plant. When interviewing a facade

engineer in practice, it appears that building service engineers are responsible for minimizing heat transfer, allowing natural light in and optimizing solar gains. MEP (mechanical, electrical and plumbing services) then use hand-calculation to check the results. Equations used by MEP are from Australian standards, CIBSE or ASHRAE etc.

Hence, a method that will have all the good sides of the existing methods is needed for this project. There is a need to develop a new simplified method to assess annual energy performance of facades considering the most important parameters which will include internal gains and ventilation loss in office buildings.

3.4 State of art of dynamic thermal models

Dynamic simulation programs help designers to carry out far more complex and precise modelling work. In order to comply with the building regulations, all new built non-domestic buildings have to meet the target emission rate. Target emission rate is calculated by using accredited computer simulation programs which can develop a reference building using notional building configurations and create a proposed building model. Predicted CO₂ emissions of proposed designs have to be lower than that of the reference buildings. The government developed Simplified Building Energy Modelling (SBEM). These tools are first used to shown compliance with the government's energy regulations. But far more importantly can be used to improve buildings energy efficiency. Other software programs with great capacities are also available and are used in day to day engineering practice.

3.4.1 Simple cyclic (admittance) method - CIBSE Guide A

The CIBSE admittance method is a standard calculation method which can be used to determine steady-state heat loss, and space cooling load. The admittance method is useful as an aid to understanding thermal response and the effect of solar control devices however it is more suitable for predicting internal temperatures after a sustained period of hot weather so may predict unrealistically high internal temperatures under more normal conditions. It is still used for the calculation of design cooling load for conventional air conditioned buildings and calculation of overheating risk in early stage assessment.

CIBSE Guide A gives guidance on load calculations and sizing the plant. It includes a steady state model for calculating heat losses, and a simple cyclic model (dynamic) which can make rapid assessment of summertime temperatures (or overheating risk) for naturally and mechanically ventilated buildings and space cooling loads. The simple cyclic model, also known as the admittance method constitutes a simple representation of a highly dynamic process and can be carried out manually. It uses a sequence of identical days for which the external conditions vary on 24-hour cyclical basis, hence it is only suitable for applications that require an assessment of conditions after a long period of identical days. It uses a steady state approach for the 'mean' values in combination with a dynamic part (eg. thermal mass) that describes all deviations from steady state, i.e. the 'swings'. The method involves heat balance equations for both steady state and for the deviations from the mean and assumes that all thermal dynamics can be represented by this equation. (Hensen et al. 2004).

3.4.1 SBEM

Simplified Building Energy Modelling (SBEM) developed by BRE, is used for non-domestic buildings in support of the National Calculation Methodology (NCM), the Energy Performance of Buildings Directive (EPBD) and the Green Deal. SBEM is a computer program that provides an analysis of a building's energy consumption. The purpose of SBEM and its interface iSBEM is to produce consistent and reliable evaluations of energy use in non-domestic buildings for Building Regulations Compliance and for Building Energy Performance Certification purposes. Although it may assist the design process, it is not primarily a design tool. It does not calculate internal temperatures, for example, SBEM calculates monthly energy use and carbon dioxide emissions of a building given a description of the building geometry, construction, use and HVAC and lighting equipment. It was originally based on the Dutch methodology NEN 2916:1998 (Energy Performance of Non-Residential Buildings) and has since been modified to comply with the recent CEN Standards. Details of the calculation method, the algorithms used and the assumptions made are provided in the SBEM Technical Manual (NCM 2017).

3.4.2 Dynamic simulation program

Building energy simulation programs are transient/dynamic simulation models which can predict the response of a building to real sequences of weather data and loads. Outcomes are predictions of energy demand, energy consumption, CO₂ emissions of buildings. The programs can also be used for natural ventilation analysis, plant sizing, analysis of energy conservation options and energy targeting. Because the programs can help engineers to show compliance to the current building regulation, they are used as decision making tools at the early designing stages.

Dynamic simulation modelling aims to model the real building performance and allows the influences of numerous thermal processes occurring in the building, their timing, location and interaction to be properly accounted for. Dynamic Simulation Modelling can predict building performance by modelling an entire building to provide detailed air movement, temperature and energy predictions.

A dynamic simulation model is a sophisticated representation of a building based on the relevant construction material properties, glazing properties, shading and internal gains. It is subjected to appropriate boundary conditions including measured mean wind pressure coefficients and suitable weather data. The building is zoned according to the layout, internal gains, systems and control strategies. Bulk air movement

throughout the model is calculated simultaneously with the thermal calculations making a fully integrated dynamic model including the effect of building storage and response. DSM is generally used to solve time-related issues with simulations often run for a whole year. Hourly data for a whole year (8760) is used.

DSM can be used for both new and existing buildings. DSM allow users to investigate the factors that can influence building thermal behaviour which include thermal insulation, thermal capacity, glazing properties, built form and orientation, climate, shading from nearby buildings, infiltration, natural ventilation, mechanical ventilation, solar gain, gains from lights, occupants and equipment, control set points, heating and cooling plants characteristics and schedules, boiler and heat pump performance.

Accredited programs also comply with the National Calculation Methodology and up to date Building Regulations such as Part L 2013. Well established software includes EDSL Tas (EDSLTas 2017), IES VE virtual environment(IES 2015), EQuest (eQUEST 2017)and Energy Plus(NREL 2017). And there are more new building simulation software being developed (Buonomano et al. 2014).

Crawley et al. (2008) provides an overview of comparison of the features and capabilities of twenty major building energy simulation programs based on the information provided by the developer. EDSL Tas and IES are commonly used in UK practices. EDSL Tas combines dynamic thermal simulation of the building structure with natural ventilation calculations. It includes advanced control functions on aperture opening and the ability to simulate complex mixed mode systems. EDSL Tas has 20 years of commercial use in the UK and around the world. IES <Virtual Environment> is an integrated suite of applications linked by a common user interface. The package includes programs such as Apache Sim which models the thermal performance of buildings, life-cycle energy and cost analysis and so on. Energy Plus is developed in the United States and is recognized as one of the most powerful thermal modelling tools. It requires large amount of data input. Design Builder which is a user interface has been developed in order to make the simulation process easier for users. Energyplus, EDSL Tas and IES VE are all suitable for more complex building forms. The author found that even among the 'mature' tools, there was not a common language to describe what tools could do.

Figure 3.5 shows the workflow of using Energy Plus and it is applicable in most of the other building simulation programs.

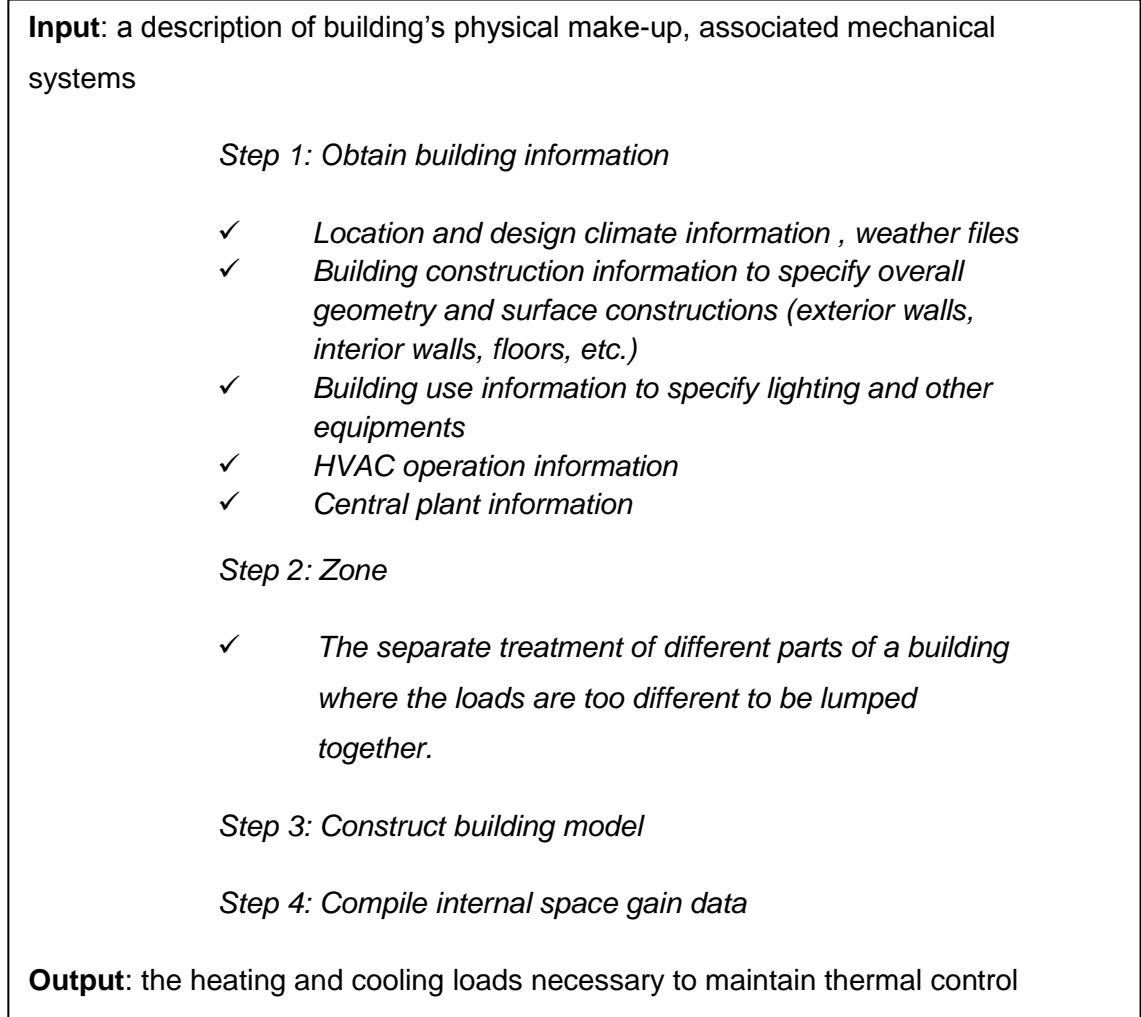


Figure 3.5 Workflow of dynamic simulation program

Optimization algorithms have been shown to be effective in identifying good solutions for the design of efficient building services. Building energy simulation tools such as Energy Plus now have optimization functions which can vary the construction of facade system to reach an optimized solution in a particular case. Zemella et al. (2011) used Neural Network Design (ENN-Design) to drive the design of a typical facade module for an office building. Single-objective and multi-objective optimization were carried out. Sensitivity analysis and Monto Carlo simulation has been adopted in building services or building envelope design.

These optimization algorithms are great for finding the optimal solution, however great attention is still needed to review simulation results. As the aim of the work in this thesis is to spot the underlying reasons for different responses of buildings to different internal and external conditions, optimization is not used here.

Limitations of dynamic thermal modelling

Using these programs to simulate the energy performance can be a time consuming process. But they are very useful in simulating the real world weather situation, especially solar radiation as well as simulating the dynamic properties of buildings.

While these programs seem to have great capabilities, there are some problems. Because of the large number of programs, it has been found that the results vary between these programs which can lead to uncertainty in design. The variability can be caused by a user's skill and accuracy of data input, applicability of the tool to the specific scenario and the calculation method used in the tool (Raslan et al. 2009). Energy simulation software use a variety of calculation methods and all of them produce different results.

Some people have described these programs as a computer black box because the users do not know what exactly is going on during the simulation process. Experienced mechanical engineers who have been using these programs for a long time still might not fully master these programs. It has also been found that there is a big gap between the predicted energy usage and actual building performance.

Computer simulations rely on detailed and accurate information in order to obtain meaningful and useful results. Example of inaccurate data includes weather data, and U-values. Moreover, operational assumptions are unlikely to match those assumed in the model. Weather data used in modelling is drawn either from the past or based on future projections. Usually designers use weather data at the closest available location,

which is another source of error. Some weather data might be estimations based on statistics. Published U-values for walls, roofs, windows, etc., are only accurate to around 10%.

Other modelling constraints include the lack of ground temperature data. The U-value of the floor and the ground immediately under the floor is extremely difficult to evaluate. Infiltration leakage (through fabric, opening doors, stack effect from escalators and lift wells etc.) can cause energy consumption variations of 5-10% but it is hard to model. Virtually all commercially available energy simulation programs assume temperature is constant within a zone (i.e. no allowance for stratification and temperature variation due to air movement etc.). Other practical reasons for discrepancies include: actual insulation properties rely on good practice, thermal bridge, colour and finish or even dirt and corrosion of surfaces affect insulations' physical properties.

It can be concluded that estimated annual energy demand of a building in absolute values can never be accurate enough to match the subsequent measured values in any year. Although building simulation program are not accurate in absolute numbers, they are good for comparison purposes.

3.4.3 Dynamic calculation principles, EDSL Tas

EDSL Tas is used in this study because the student licence and teaching were available to the author. Equation 8 shows the principal simulation theory of Tas: conservation of energy (as represented by the energy balance equations), requires that the sum of the gains and losses within a zone for each hour should be zero.

$$Q^{plantS} + Q^{sol} + Q^{light} + Q^{occS} + Q^{equS} + Q^{inf/vent} + Q^{BHT} + Q^{AM} + Q^{cond(op)} + Q^{cond(transp)} = 0$$

Equation 8

Q^{plantS} , *Plant*, is the total power input from the plant (the sum of radiant and convective portions).

Q^{sol} , *Solar gain*, is the sum of the *surface solar gains* for all the surfaces facing into the zone.

Q^{light} *Lighting gain*, is the power input from lights (sum of radiant and convective portions).

Q^{occS} *Occupancy gain*, is the sensible power input from occupants (sum of radiant and convective portions).

Q^{equS} , *Equipment gain* is the sensible power input from equipment (sum of radiant and convective portions).

$Q^{inf/vent}$, *Infiltration/ventilation heat gain*, represents the heat gained (or if negative lost) by the zone due to the exchange of air between the zone and the external environment:

Q^{BHT} , *Building heat transfer*, represents the sum of heat gains from 2 sources: 1) heat entering the zone from *Link*, *Null Link* or *internal* building components, and 2) heat released into the zone which had been temporarily stored in the air (this quantity is positive when the air temperature is falling and negative when it is rising):

Q^{AM} , *Air movement*, represents heat gained via specified inter-zone air movement flows and via air movement through apertures linking to other zones:

$Q^{cond(op)}$, *External conduction (opaque)* is the heat gained by conduction through the inside surfaces of exposed opaque components and ground floors:

$Q^{cond(transp)}$, *External conduction (glazing)* is the heat gained by conduction through the inside surfaces of exposed transparent components:

Tas solves the sensible heat balance for a zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is solved simultaneously to generate air temperatures, surface temperatures and room loads. This procedure is repeated for each hour of the simulation.(EDSLTas 2015)

The energy flows are broken down into the following categories: plant input, solar gain, lighting gain, occupancy gain, equipment gain, infiltration and ventilation, building heat transfer, external conduction (opaque components), external conduction (transparent components). Positive values indicate a heat gain and negative values a heat loss. The Sensible Load Breakdown facility provides an hourly breakdown of sensible heat flows into and out of a zone or group of zones. These figures represent a balance account of energy entering and leaving the zone in question. For this purpose the boundaries of the zone are the inner surfaces of its walls, windows, floors and ceilings.

The sum of the gains and losses for the zone in question over the whole 24 hour period is displayed as Net Imbalance. This figure is a measure of the accuracy of the numerical algorithms employed within Tas. Typically this figure is less than 0.002 kWh.

EDSL Tas is a more far more sophisticated modelling method than the steady-state method. Among many other major differences, such as hourly simulating capability, it can be seen in Equation 8 that Tas calculates for thermal mass of the internal building elements as well as the thermal capacity of the air which is not included in the steady-state calculations. EDSL Tas can also model the solar gains more accurately: gains are modelled by resolving them into radiant (distributed amongst the zone's surface) and convective portions (injected into the zone air).

3.5 Proposed framework of assessment

After describing the currently available methods for calculating building energy demand, highlighting their advantages and disadvantages, and realising that design is an iterative and complex process which needs a good plan to generate useful results, a framework of assessment was developed to investigate the research questions mentioned at the beginning of this chapter. Figure 3.6 shows the proposed assessment framework which is based on the recommendation contained in CIBSE Guide A.

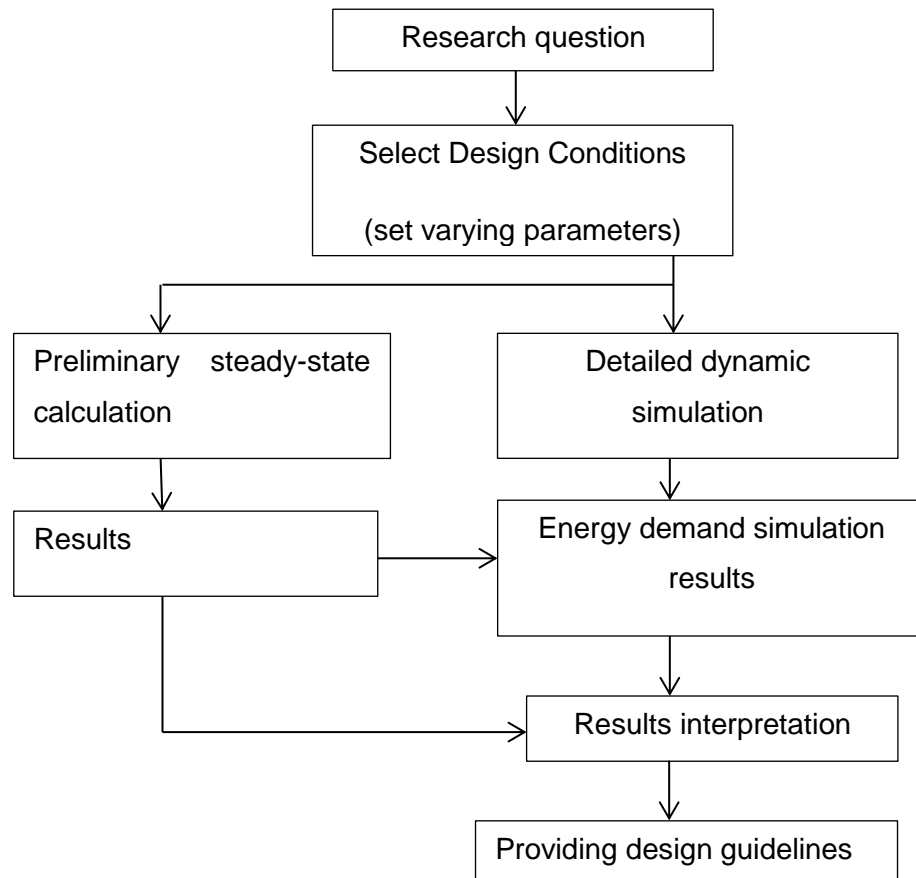


Figure 3.6 proposed Assessment framework for this project

Generally, past studies on this subject have compared the performance of different types of glazing by calculating the associated heating and cooling demands. Demand can be converted to annual energy consumption and then CO₂ emissions. In this study, energy demand for heating and cooling is used as a performance indicator of office facades.

Model set up

The model used to investigate facade performance should be capable of representing a large percentage of relevant building stock. The target building type in this work is large scale office buildings with simple shapes, either rectangular or square and high rise. It should also allow energy use to be estimated using both static (i.e. hand) as well as dynamic (i.e. software) simulation methods. It was felt that this could mostly easily be achieved by using the model shown in Figure 3.7. The model studies the perimeter zones of a high rise building. Perimeter zones are worth investigating because it is an area that facade affect the most, and where the most amount of heat transfer occurs.

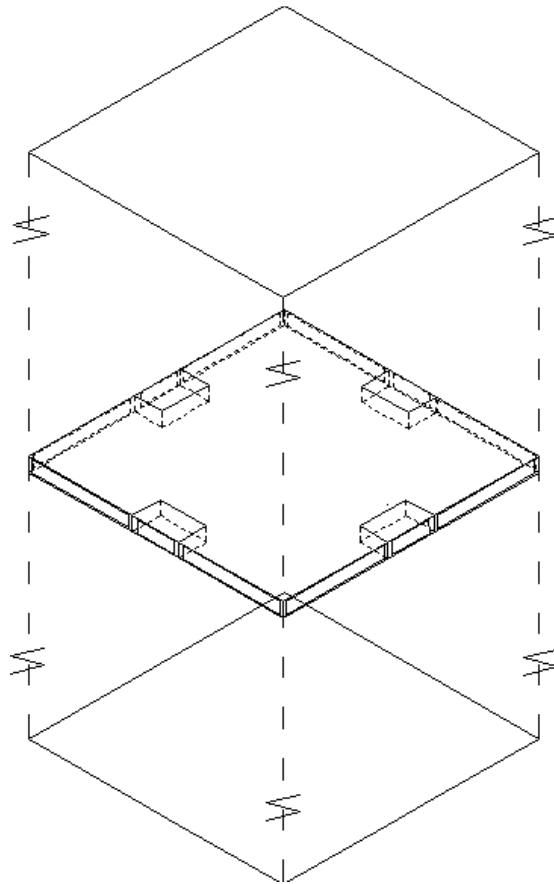


Figure 3.7 Building model

Methods

In this project both hand calculations and computer simulation will be carried out. Hand calculations will show the fundamental principles to avoid 'computer black box'. It generates indicative figures and educates the users of the impact of the most significant parameters on heating and cooling demand. It can also be counted as

primary test to avoid blunders and set up a framework to analyse detailed simulation results.

Computer simulation will give whole year energy prediction but takes more effort to run and contain a large level of uncertainty. The results from the hand calculation method can be compared to the outcomes of the simulation programs to see if similar trends can be achieved. The results will be useful for developing general guidelines for a range of climate conditions.

Results presentation and interpretation

The ultimate aim is to provide facade design guidelines in different climate conditions. Dynamic simulation program needs to be used correctly to generate more accurate and reliable results to show the effect of facade performance. Results should be analyzed in a way that underlying reasons of behaviors in difference climates can be underpinned. Graphical presentations should be clear and informative in order to provide information for engineers and architects

3.6. Proposed steady-state method

3.6.1 Building model set up

A model is set up as a single office space on an intermediate floor with one external facade. The width of the unit is 10m and the depth is 6m. This model represents a typical office module and was used by Kolokotroni et al. (2004).

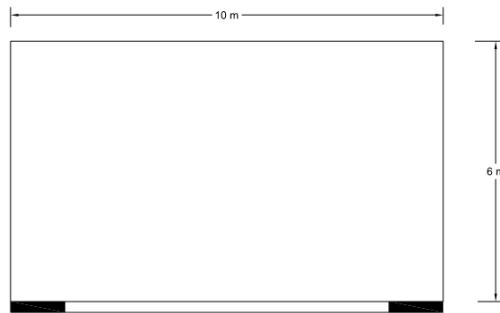


Figure 3.8 Plan view of the Model

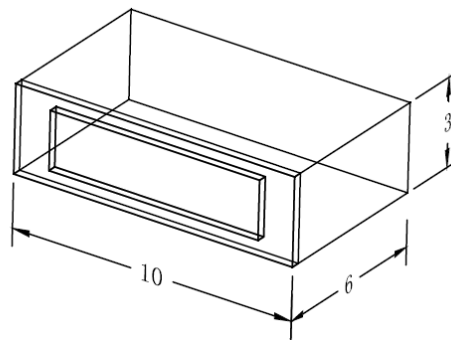


Figure 3.9 3-d view of the model room, with one side of external facade

Assumptions made are as follows,

- 1) There is no external solar shading
- 2) It is light weight facade structure

3.6.1 Proposed steady-state hand method

The proposed method, as shown in Equation 9, uses the heat balance equation which includes conduction heat gain/loss, solar gains, internal gains and heat exchange due to air exchange (ventilation and infiltration) which are all significant in office buildings. A working example is included in Appendix 1.

$$Q = Q_{cond} + Q_{air} + Q_{int} + Q_{sol}$$

Equation 9

Where

Q_{cond} is the total conductive heat flow through building envelope = $\Delta T \sum_k U_k A_k$,

Q_{air} is the heat gain/loss due to air exchange (infiltration and/or ventilation) = $\rho c_p V \Delta T = \frac{1}{3} NV \Delta T$

Q_{int} is the internal heat gains from office lighting, equipment and occupants = $Q_{lit} + Q_{equ} + Q_{occ}$

Q_{sol} is the heat gain from solar radiation = $g A_w S_o$

in which,

ΔT is the difference between the exterior and interior temperature = $T_{out} - T_{in}$

U_k is the thermal conductance of the external envelope element k

A_k is the area of the external envelope (m^2)

A_w is the area of the window (m^2)

V is the volume of the room (m^3)

S_o , incident solar irradiance on the window (W/m^2);

Hence, the variables involved in this equation are:

- Average temperature difference between indoor and outdoor (ΔT)
- Solar irradiance (S_o)
- U-value of windows (U_g)
- U-value of wall (U_w)
- Area of the external envelope (A)
- Area of the window (A_g)
- Area of the wall (A_w)
- g-value

3.6.2 Design conditions and input parameters

Table 3.4 shows values of the other test parameters assumed in the simulations. The standard ventilation rate and internal gains were taken from CIBSE Guide A (CIBSE 2015) assuming the density of occupation is 12m² per person. The overall U-value of the facade was assumed to vary between 1.2 and 2.6 W/m²K. The higher value was selected based on recommendations in Part L2A of the UK Buildings Regulations (DCLG 2013) which states that the U-value of curtain walling should in general not exceed 2.2 W/m²K but can be as high as 2.7 W/m²K in buildings with high internal gains. The lower value is based on manufacturer's literature which shows that walling with a U-value of 1.1 W/m²K and lower is now available. Three levels of g-value, namely 0.3, 0.4 and 0.5, were investigated in this study. All the glazing was assumed to be low-e double glazing. The effect of latent heat was not considered in the simulations.

Model	3m × 10m × 6m; 3m × 10m face is external facade and other faces are internal partitions	
Window to wall ratio	0.7	
Internal gains (W/m ²)	People	6.7
	Lighting	12
	Equipment	15
Ventilation rate	10 l/p/s	
Operating hours	0800 -1800, 7 days	
Wall constructions	Glass and spandrel U-value	1.2-2.6 (0.2 increment)
	g-value	0.3,0.4,0.5

Table 3.4 Test parameters

Weather data input

For the steady-state calculation, seasonal average values of outdoor temperature and average solar radiation incident on each facade of the building are needed. This section explains how these data are obtained. This is because in the temperature profiles of the northern hemisphere, most of the cities experience higher/warm temperatures in the summer months which are June, July, August and September, and relatively cooler temperatures in the winter months which covers January, February, November and December. The temperature of the transition months, or mid-season months, March, April, May and October, are lying in between. Therefore, in order to compare the climate characteristics and simplify the hand-calculation process, a year is analysed in three seasons. Details of climate data collections are described in section 3.8.2.

3.7 Tas simulation outline

EDSL Tas is a commercially available software, developed by EDSL. It is accredited by the UK government and can be used to estimate the annual load due to heating, cooling, lighting and ventilation of buildings. Tas models hourly energy requirements and can be used to analyse the performance of whole structures. TAS allows designers to predict energy consumption, CO₂ emissions, operating cost and occupant comfort. 'It calculates the heating and cooling load resulting from inside and outside buildings. The program adopts the mechanical simulation principle by tracking the thermal behaviour via various snapshots taken every hour. This gives users a detailed image of the way the building performs (Ahmed 2011).' Tas Program has been compared with test room data by International Energy Agency (IEA). The actual data is found to be higher than predicted given detailed hourly weather data was collected at the testing site. The program is based on DSM.

Tas contains three parts: TAS 3D Modeller, TAS Building Simulator and TAS Results Viewer. In TAS 3D Modeller, users construct geometries of building models which include the basic features such as walls, windows and roof. Thermal zones are assigned in this stage.

3.7.1 Tas building model

A comparable model is set up in Tas. Figure 3.10 shows the layout of the building model used in this work. It is essentially a square, three-storey structure with an area 55m×55m per floor and floor and floor to ceiling height of 3m. The structure is actually a simplified model of a tall, multi-storey office block and assumes that all the floors apart from the top and the bottom consume similar amounts of energy (Korolija et al. 2013). For each side of the exterior wall, there are three windows. There are one large window span in the middle and two small windows at each side of the large window. The overall window-to-wall ratio is 0.7.

Energy usage was assessed by considering the performance of four perimeter offices: 1, 2, 3 and 4, 6m deep × 3m high × 10m long, which were assumed to be located on the middle floor and face respectively West, North, East, and South. It was assumed that the long face forms the external facade and the window to wall ratio is 0.7. The remaining three sides of the room are internal walls, and, as such, the effect of adjacent offices on the performance of the test offices are minimal. These four zones are spaces of around 60m² with one external facade and three sides of internal

partitions. This way of modeling can provide a comparable model with the steady state hand calculation method.

The roof is flat and opaque with no roof windows. There is no external shading in this model.

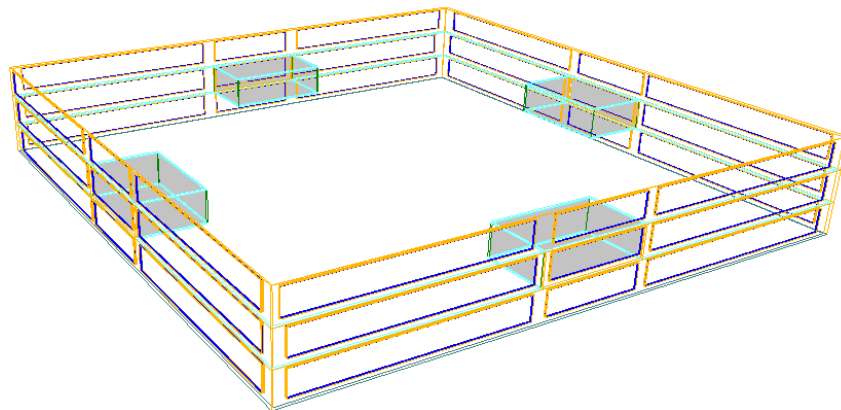
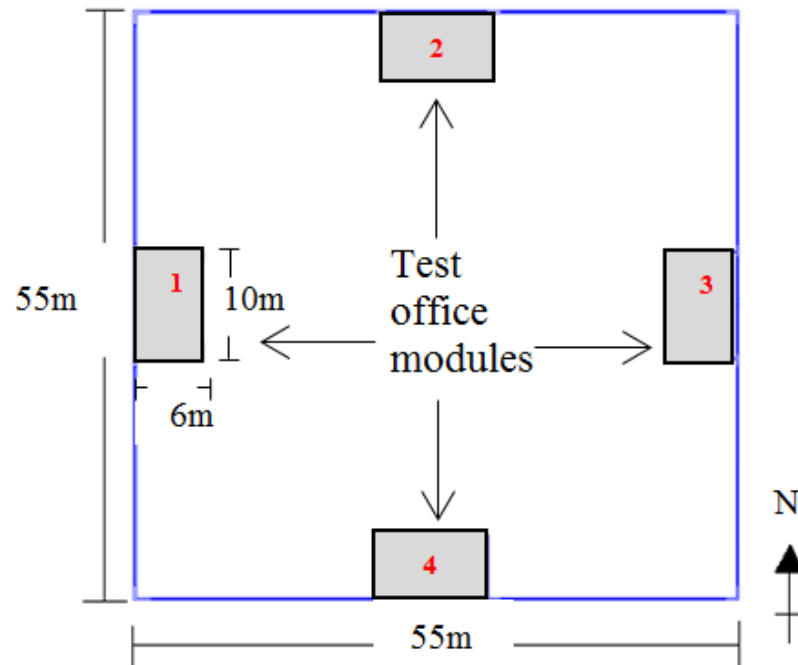


Figure 3.10 TAS Building model

The built 3-D model of the building was then checked against construction errors by the Tas system automatically before being exported to the Tas building simulator.

3.7.3 Input parameters

The building modelled then can be exported to TAS building simulator where users can feed in data for:

- 1) Weather data
- 2) Construction materials
- 3) Internal conditions
- 4) Schedule

1) '**Weather database**' in Tas Building Simulator has a number of built-in past weather data for some UK locations such as London Heathrow and so on. Weather files include hourly data for a year for global solar radiation (W/m^2), diffuse solar radiation (W/m^2), cloud cover (0-1), dry bulb temperature ($^{\circ}\text{C}$), relative humidity (%), wind speed (m/s) and wind direction($^{\circ}$). Weather data for more locations can be imported and used in TAS Building Simulator.

For simulation programs, appropriate weather files are needed for the purpose. For current climate conditions, one needs to find the prevailing weather data which can represent the current situation. On the market, there is a large pool of weather data available. Hence choosing a reasonable set of climate data is important. Incorrect weather data can either make the building easier to reach the compliance level or more difficult. If it is the latter case, the designer might spend more effort on using more costly energy efficient strategies to meet the compliance when they are actually not needed.

There are a number of formats: CIBSE standard, EDSL TAS, EPW - industry standard weather format developed for the U.S. Department of Energy's 'Energy Plus' simulation software and used by more than 20 of the leading energy software packages worldwide

Current UK data is available from CIBSE, Test Reference Year (TRY) and Design Summer Year (DSY), which is used for UK building regulations. The Test Reference Year (TRY) is hourly data for twelve typical months. The data is selected from around 20-year data sets (typically 1983 -2004) to produce a continuous 1-year sequence of data. This set of data represents typical weather conditions. Hence this set of data is better than a single year weather file which may not be able to present the weather characteristics.

2) Construction materials

TAS Building Simulator has some useful built-in construction database such as the Notional Building. Users can also modify the built-in database or create new constructions.

a) Glass settings

As introduced in section 2.2.4, designers are becoming ever more aware of the importance of controlling incoming solar radiation through windows. Low g-value windows are available on the market and can be as low as 0.18, the highest being 0.7 (see Table 2.4). However, glass with an extremely low g-value of 0.18 have a low visible light transmittance of 0.3, which will increase the energy needed for lighting. Therefore, a g-value of 0.3 was chosen as the lower limit of this study, as its visible light transmittance is 0.5. The UK's Building Regulations Part L2A, Criterion 3, sets 0.68 as the g-value limit for side-lit windows facing east. In the national calculation methodology, a notional building has low-emissivity side-lit windows with a g-value of 0.4, and visible transmittance of 0.7. As the engineers will always select better windows than that of the notional building, the windows investigated in this study include low-e glass and has a g-value of 0.3, 0.4, or 0.5.

However, g-value is a combination effect of transmittance, reflectance and absorptance. These values have been varied to generate the required g-value. Details of the customised glass panes are shown in Table 3.5 and Table 3.6.

Light		Solar Energy				Pilkington Shading Coefficient			U-value
Transmittance	Reflectance	Direct Transmittance	Direct Reflectance	Direct Absorptance	Total Transmittance (G value)	SW	LW	Total	
0.714	0.101	0.233	0.296	0.471	0.3	0.268	0.076	0.344	1.521
0.712	0.103	0.33	0.301	0.368	0.4	0.379	0.082	0.461	1.527
0.714	0.101	0.422	0.31	0.269	0.5	0.485	0.090	0.575	1.521

Table 3.5 TAS testing glass properties

g	layer	Material	Width (mm)	Solar Trans.	Ext. Solar Refl.	Int. Solar Refl.	Ext. Emis.	Int. Emis.	Conductivity	Convection coefficient	Vapour Diffusion factor
0.3	inner	glass	6	0.78	0.07	0.07	0.84	0.84	1	0.001	9999
	2	glass argon layer	12	0	0	0	0	0	0.01	1.9	1
	3	glass	6	0.29	0.29	0.41	0.84	0.04	1	0.001	9999
0.4	inner	glass	6	0.783	0.072	0.072	0.837	0.837	1	0.001	99999
	2	glass argon layer	12	0	0	0	0	0	0.01	1.9	1
	3	glass	6	0.409	0.289	0.414	0.837	0.042	1	0.001	99999
0.5	inner	glass	6	0.78	0.07	0.07	0.84	0.84	1	0.001	9999
	2	glass argon layer	12	0	0	0	0	0	0.01	1.9	1
	3	glass	6	0.525	0.29	0.41	0.84	0.04	1	0.001	9999

Table 3.6 Glass properties

Problems encountered while varying g-values

G-value is a combination of a part of absorption which is emitted into the interior space and the direct transmittance. Pilkington Shading Coefficient separates the total shading coefficient to short wavelength shading coefficient (SWSC) and longwave shading coefficient (LWSC). It has been found that a different combination of direct transmittance value and absorptance value, even they give a same overall g-value, will lead to a different building energy consumption. In other words, the energy consumption results are sensitive to the individual changes in emissivity, direct transmittance, absorptance. This raises the question: the building regulation and also, most of the work done in the past literature only highlight the importance of assessing the optimum g-value. Two types of glasses with the same g-value would give different energy performance depending on their detailed glass configurations. Hence, there is a need to perform a sensitivity analysis to these individual parameters.

b) Insulation properties

Curtain walling is classed as glazing in building regulations. In the UK's Building Regulation 2010, the current maximum allowable U-value for curtain walling is 2.2 W/m²K. However, the regulation also states that the U-value limit of glazing can be increased to 2.7W/m²K if there are high internal heat gains in buildings. On the other hand, high performance curtain wall products, which are composed of high performance insulation materials and double or triple glazing systems, can achieve a U-value of 1.1 W/m²K. This U-value is well below the U-value used in the notional building in the UK's national calculation methodology, which is 1.6 W/m²K. Therefore,

in the present study, U-value was varied between 1.2 and 2.6 W/m²K, with a 0.2 increment.

In TAS, the properties of the insulation materials can be changed. Table 3.7 shows the variation in the insulation in the opaque panel of the modelled high performance facade to reach the overall U-value of the curtain wall, from 1.2 to 2.6 W/m²K with 0.2 increments. It can be seen that the conductivity of the insulation and the width of the insulation are varied to achieve the desired U-value.

	width	conductivity	Convection	Vapour D	density	specific heat capacity
ref1	15	0.02	0.001	0.001	180	800
ref3	13	0.03	0.001	0.001	180	800
ref4	8	0.03	0.001	0.001	180	800
ref5	5	0.03	0.001	0.001	180	800
ref6	3	0.03	0.001	0.001	180	800
ref8	5	0.08	0.001	0.001	180	800
ref7	2	0.08	0.001	0.001	180	800

Table 3.7 TAS varying insulation properties

3) Internal conditions settings allow users to set levels of internal gains, thermostats etc. choose system parameters.

Internal heat gains are based on the values given in CIBSE Guide A. Assuming the test office has a medium density of 12m² per person, the heat gains from occupants will be 6.7 W/m², 12 W/m² from lighting and 15 W/m² from equipment. Therefore, the total amount of the internal heat gain will be 33.7W/m².

If heat-emitting LED lighting is used, the heat gain from lighting can be reduced to 4-5 W/m². CIBSE (2015) found that the heat emission coefficient of LED lighting can be significantly lower than other lighting. The lower internal heat gain scenario in this study will be set as 24W/m²K.

Humidity has been set at default value, as 0-100%, because it does not influence the heating and cooling load of buildings and hence is not studied here.

4) Schedule can be set as desired working hours. These will be set as to the desired values.

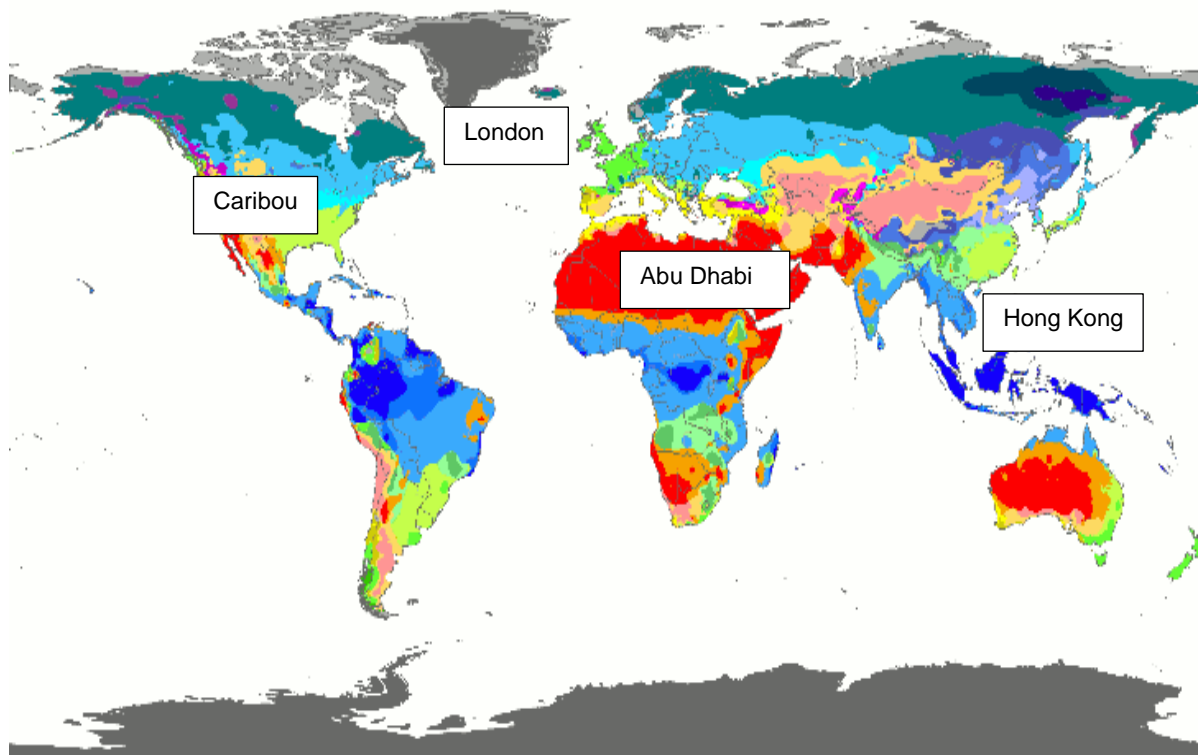
3.8. Overview of tests

In order to investigate the influence of high performance facades on energy demand of office buildings under different climates and internal conditions, this section sets out a test programme which would be carried out to answer the research questions.

3.8.1 Location selection

As discussed before, the external climate condition is one of the key factors influencing facade energy performance. Study locations are needed to cover a range of climatic zones. London and Hong Kong are selected because both cities have a high density of office buildings but quite different climates. Conventionally London is thought to have a cold climate and heating is the dominant load whereas Hong Kong is thought to have a warm climate and cooling is needed. It is also important to look at cities which have more extreme climatic conditions, i.e. extremely cold and extremely hot.

In order to have a better understanding of the climate types of the global environment, the Koppen- Geiger classification system is looked here. The Koppen-Geiger climate classification is based on annual and monthly averages of temperature and precipitation. It is widely used as an authoritative map of the world climates, shown in Figure 3.11. As shown in Figure 3.11 and Table 3.8, there are five major climate zones labelled by the first five letters of the alphabet. Within each climate zone, there are a number of subtypes distinguished by letters (Peel et al. 2007). It can be seen that London falls in the Cfb which is a marine west coast climate. Hong Kong is Cwa which is a monsoon-influenced humid subtropical climate. The eastern part of China which is the more developed part of the country has climate types C and D whereas in Europe the climate is in typically types C.



Af	BWh	Csa	Cwa	Cfa	Dsa	Dwa	Dfa	ET
Am	BWk	Csb	Cwb	Cfb	Dsb	Dwb	Dfb	CF
Aw	BSh	Cwc	Cfc	Dsc	Dwc	Dfc	Dfd	
BSk				Dsd	Dwd	Dfd		

Contact : Murray C. Peel (mpeel@unimelb.edu.au) for further information

DATA SOURCE : GHCN v2.0 station data
Temperature (N = 4,344) and
Precipitation (N = 12,396)

PERIOD OF RECORD : All available

MIN LENGTH : ≥30 for each month.

RESOLUTION : 0.1 degree lat/long

Main Climates	Precipitation	Temperature
A: equatorial	W: desert	h: hot arid
B: arid	S: steppe	k: cold arid
C: warm temperate	f: fully humid	a: hot summer
D: continental	s: summer dry	b: warm summer
E: polar	w: winter dry	c: cool summer
	m: monsoonal	d: extremely continental
		F: polar
		T: polar

Figure 3.11 Koppen Climate Classification (Peel et al. 2007)

Koppen Climate Type	Description	Representative cities
A	Tropical moist climates: all months have average temperatures above 18 degree Celsius	Singapore
B	Dry climates: with deficient precipitation during most of the year	Abu Dhabi, Phoenix
C	Moist mid-latitude climates with mild winters	London, Hong Kong
D	Moist mid-latitude climates with cold winters	Estonia, Norway, Moscow, Caribou,
E	Polar climates: with extremely cold winters and summers	

Table 3.8 Koppen climate types

To further illustrate the climatic characteristics of different climates in terms of temperature, Figure 3.12 shows the monthly average temperature profiles of a few popular cities which represent mild or extreme climates. It can be seen that Abu Dhabi (Bwh) and Singapore (A) form the upper bound of the temperature profiles whereas Caribou (Dfb) and Moscow are in the lower bound of the profile. In order to investigate the benefits of high performance facades in different climate conditions, it reasonable to look at locations which experience the extremes of temperatures and some locations with mild climatic conditions.

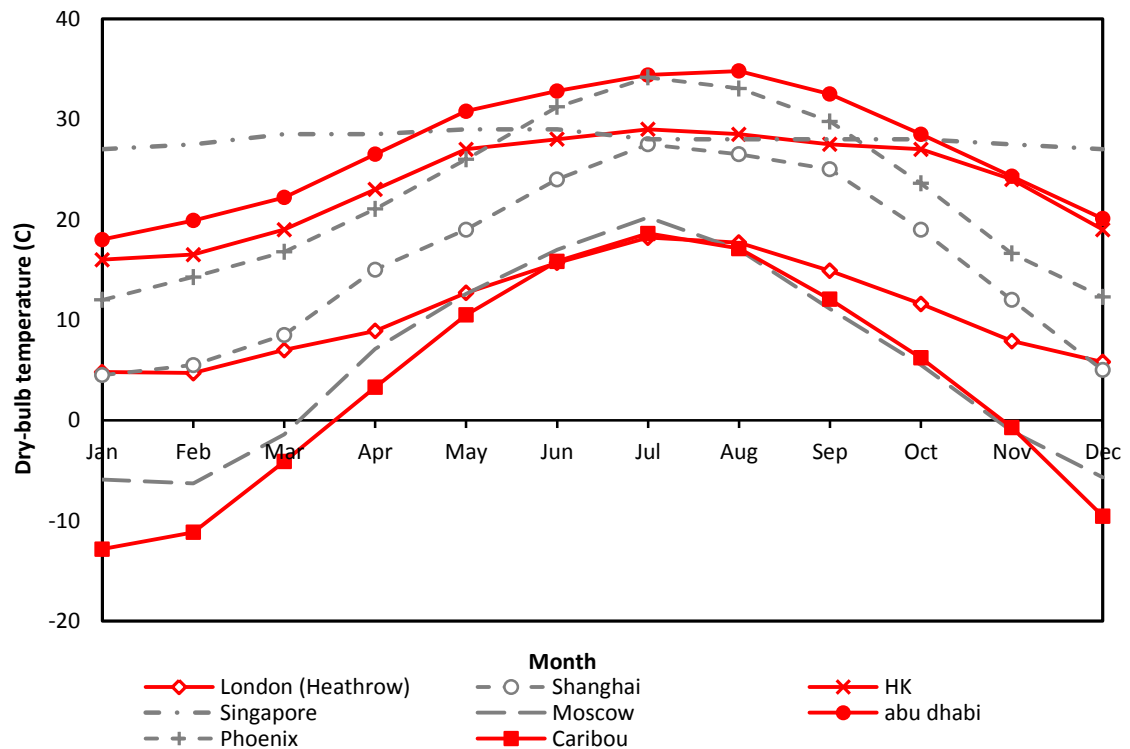


Figure 3.12 Monthly temperature profile of representative cities.

Data availability

During the process of selecting the locations, one problem encountered is that monthly average solar irradiance data on vertical surfaces facing different orientations needed for the steady-state calculation are not easily available for international locations. Most of the solar data available from current studies and online resources are hourly global and diffuse irradiation on horizontal surfaces. This needs to be converted into the corresponding components of irradiation on inclined surfaces. A few authors have proposed mathematical models to perform these conversions however it is time consuming and it is another research area. The U.S. has published monthly average solar irradiance data on vertical surfaces for all of its cities. Therefore, for convenience, Caribou, Maine, U.S. has been selected to represent a colder climate compared with London. Abu Dhabi has been selected to represent the extreme hot climatic conditions.

Selected cities, namely, London, Hong Kong, Caribou and Abu Dhabi have cold, mild cold, hot and extreme hot climates. London has a temperate climate with mild winters and cool summers. Hong Kong is closer to the equator and has a humid subtropical climate with typically warm winters and hot summers. Caribou has colder winters than London and warm summers. The locations of these four cities are marked in Figure 3.11. Table 3.9 summarizes the climate characteristics of these four locations from Koppen climate classification systems.

	Koppen Climate classification	Characteristics
Abu Dhabi	Bwh: arid hot desert	hot, sunny and dry
Hong Kong	Cwa: temperate climate with dry winters/ humid subtropical climate	humid summers, precipitation present during all seasons
London	Cfa: temperate climate with significant precipitation/marine temperate climate	changeable weather, cool summers and mild winters
Caribou	Dfb: humid continental climate	cold and snowy winters, warm summers

Table 3.9 Climate Characteristics of London and Hong Kong (Ajla Aksamija 2013)

3.8.2 Summary of weather data for hand-calculations

When we look at temperature profiles of the northern hemisphere, most of the cities experience higher/warm temperatures in the summer months which are June, July, August and September, and relatively cooler temperatures in the winter months which covers January, February, November and December. The temperature of the transition months, March, April, May and October, are lying in between. The monthly values of temperature from Figure 3.12 were used to calculate the average outdoor temperatures by season shown in Table 3.10 to Table 3.13. Equation (1) uses values of the monthly mean daily solar irradiance on vertical surfaces, S_o , in order to estimate energy usage.

Caribou	$T_{out} (^{\circ}\text{C})$	$T_{in} (^{\circ}\text{C})$	$\Delta T (^{\circ}\text{C})$	$S_o (W/m^2)$			
				N	E	S	W
Winter	-8.6	21	-29.6	24.0	51.3	119.6	49.6
Mid-seasons	4.0	21	-17.0	52.9	104.2	132.4	101.5
Summer	15.9	21	-5.1	66.4	123.6	123.6	121.6

Table 3.10 Caribou indoor and outdoor temperatures ($^{\circ}\text{C}$), solar irradiance (W/m^2), averaged by seasons

London	$T_{out} (^{\circ}\text{C})$	$T_{in} (^{\circ}\text{C})$	$\Delta T (^{\circ}\text{C})$	$S_o (W/m^2)$			
				N	E	S	W
Winter	5.8	22	-16.2	14.5	27.1	57.9	27.1
Mid-season	11.0	22	-11.0	49.4	80.8	100.7	80.8
Summer	16.6	22	-5.4	70.4	106.6	111.4	106.6

Table 3.11 London indoor and outdoor temperatures ($^{\circ}\text{C}$), solar irradiance (W/m^2), averaged by seasons

Hong Kong	$T_{out} (^{\circ}\text{C})$	$T_{in} (^{\circ}\text{C})$	$\Delta T (^{\circ}\text{C})$	$S_o (W/m^2)$			
				N	E	S	W
Winter	18.9	21	-2.1	35.4	68.2	118.8	67.7
Mid-season	24	23	1	45.8	70.8	77.1	77.1
Summer	28.3	25	3.3	57.8	87.0	65.1	89.1

Table 3.12 Hong Kong indoor and outdoor temperatures ($^{\circ}\text{C}$), solar irradiance (W/m^2), averaged by seasons

Abu Dhabi	$T_{out} (^{\circ}\text{C})$	$T_{in} (^{\circ}\text{C})$	$\Delta T (^{\circ}\text{C})$	$S_o (W/m^2)$			
				N	E	S	W
Winter	20.6	22	-1.4	-	-	189.8	106.5
Mid-season	27	22	5	-	-	125	140
Summer	33.6	22	11.6	-	-	96.6	148

Table 3.13 Abu Dhabi indoor and outdoor temperatures ($^{\circ}\text{C}$), solar irradiance (W/m^2), averaged by seasons

T_{in} = indoor design temperature ($^{\circ}\text{C}$)

T_{out} = outdoor dry-bulb temperature ($^{\circ}\text{C}$)

ΔT = outdoor temperature – indoor temperature ($^{\circ}\text{C}$)

S_0 = solar irradiance (W/m^2)

Internal design temperature (T_{in}) of London is obtained from CIBSE Guide A. It is set as 22 degree over all seasons to simplify calculation process. In addition, the highest occupant productivity in offices was found at when T_{in} is 22 degree (Seppanen et al. 2006). T_{in} of Hong Kong are slightly different because officially, Hong Kong has deliberately set it at 25 °C in summer, which is a part of HK 25.5 DEG C initiative, to help reduce energy usage over this period (Yang et al. 2008). T_{in} of Caribou is set at 21°C because Caribou is a colder country which means it needs more heating. T_{in} of Abu Dhabi, where cooling load is probably needed all year around, is set at 22 degree over all seasons because it is within the range of comfort design indoor temperature for office buildings, and the same or similar T_{in} has been used in the existing studies, for example, by Mahboob et al. (2014).

Monthly mean solar irradiance data on vertical surfaces for four orientations of these locations takes more effort to find. For London, these values, shown in Figure 3.13, were determined using the method in SAP (BRE 2012). For Hong Kong, the data was extracted from a study by Li et al. (2002). Caribou's data is extracted from the US's Solar Radiation Data Manual for Buildings (Marion et al. 1995). The solar radiation data for Abu Dhabi is from a study conducted by Jafarkazemi et al. (2013). Extracted solar data were averaged according to seasons to produce the above tables.

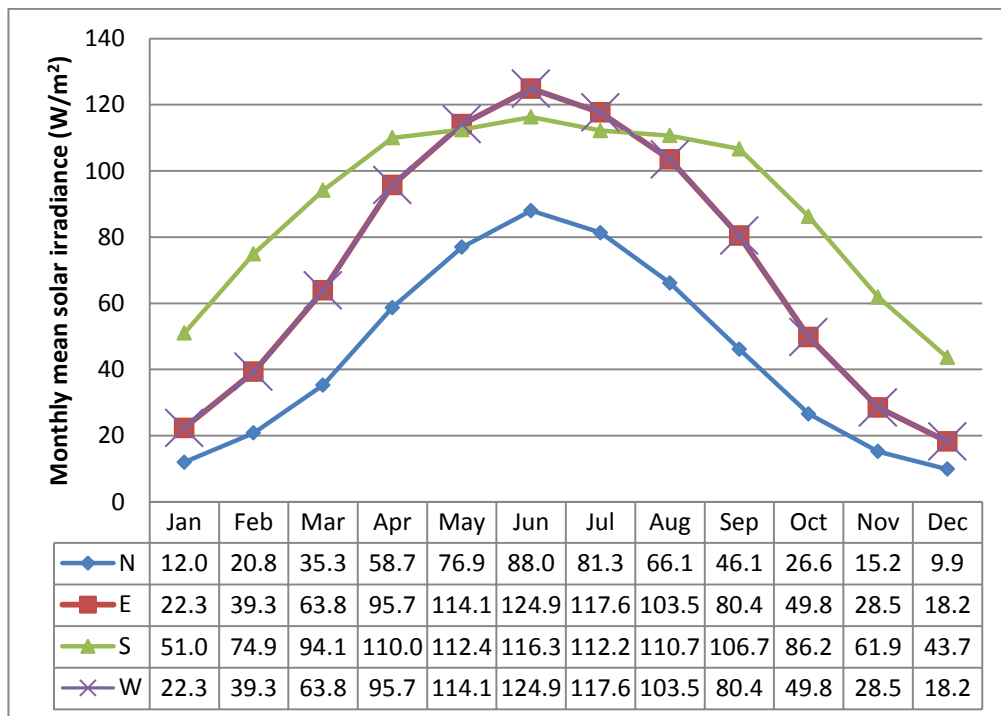


Figure 3.13 Monthly mean solar irradiance data on North, East, South and West facing vertical surfaces for London W/m^2

Comparing weather characteristics of four locations

In London, the largest temperature difference occurs in winter which is $-15.2\text{ }^{\circ}\text{C}$ and smallest in summer, which is $-5.4\text{ }^{\circ}\text{C}$ (Table 3). Note that in London the averaged outdoor temperature is always lower than indoors as indicated by the negative ΔT values. Winter months have the least amount of solar heat gains whereas summer has the highest. Mid-season is lying in between winter and summer both in terms of temperature and solar irradiation.

As shown in Table 3.12, Hong Kong has a higher temperature profile than London in all three seasons. In Hong Kong, the difference between the indoor design temperature, T_{in} , and outdoor mean dry bulb temperature, T_{out} , i.e. $\Delta T (= T_{out} - T_{in})$ is relatively small in Hong Kong compared with London. Unlike London, in Hong Kong, the outdoor temperature is higher than indoor design temperature for most of the year (i.e. mid-season as well as summer). During winter months, the solar irradiation fall on building envelopes in Hong Kong is significantly higher than that on London which means London receives little solar radiation in winter. However, for the two other bands, the solar irradiance in both cities is largely similar.

As shown in Table 3.10, Caribou experiences the coldest winter among the four selected locations, ΔT is as large as $-29.6\text{ }^{\circ}\text{C}$, almost double that of London. Same as London, averaged outdoor temperature is always lower than the indoor design temperature. The solar irradiation falling on building envelopes in Caribou is about the same as London. South orientation receives the most amount of solar radiation.

From Table 3.13, it can be seen that Abu Dhabi has the warmest climate among four locations. Abu Dhabi has a warmer summer than Hong Kong; its ΔT reaches $11.6\text{ }^{\circ}\text{C}$ which almost triples ΔT of Hong Kong. For a south-facing vertical surface, incident solar radiation peaks during winter months with an average of 189.8 W/m^2 and is decreased to minimum, 96.6 W/m^2 in summer months. For the west orientation, incident solar radiation on a vertical surface in summer is higher than that in winter (Jafarkazemi and Saadabadi 2013).

3.8.3 Overview of weather data for dynamic simulation

Weather data needed for simulation programs is a full year's worth of hourly weather data. Most of the simulation programs need hourly data of: air temperature, relative humidity, global or direct solar radiation, wind speed. Wind direction, cloudiness and rainfall are desirable but not essential to include.

Current weather data

Thus for London, the weather data used was taken from CIBSE's Test Reference Year database (CIBSE 2013). whereas for Abu Dhabi, Hong Kong and Caribou the weather data was obtained from the Energy Plus Website (EnergyPlus 2004). The US Department of Energy, Energy Efficiency and Renewable Energy provides free weather files in .epw format for international locations. Epw is Energy Plus weather file format developed from international weather sources. Weather data provided by Energy Plus are originally gathered from different institutes in different countries in their own format. For example, Hong Kong data source comes from City University of Hong Kong. These data have been all made into .epw format and can be used in leading building simulation programs including TAS and IES. Autodesk Ecotect Analysis 2011 is used to convert data from Energy Plus database into a correct format to feed into EDSL Tas. Table 3.14 to Table 3.17 show the seasonal averages of hourly weather data for these locations. These trends match with weather data obtained for hand calculation method.

London	$T_{max, (^{\circ}C)}$	$T_{min, (^{\circ}C)}$	$T_{av, (^{\circ}C)}$	$S(Wh/m^2)$
Winter	14.5	0.5	6.8	1489
Mid-season	18.2	1.7	10.5	3780
Summer	25.7	9.3	16.8	5401

Table 3.14 Seasonal averaged temperature and solar radiation data for London, Tas

Hong Kong	$T_{max, (^{\circ}C)}$	$T_{min, (^{\circ}C)}$	$T_{av, (^{\circ}C)}$	$S(Wh/m^2)$
Winter	24.1	13.5	17.7	3769
Mid-season	28.4	18.1	23.2	4008
Summer	31.9	24.4	28.2	4856

Table 3.15 Seasonal averaged temperature and solar radiation data for Hong Kong, Tas

Caribou	$T_{max, (^{\circ}C)}$	$T_{min, (^{\circ}C)}$	$T_{av, (^{\circ}C)}$	$S(Wh/m^2)$
Winter	5.9	-19.3	-7.65	3285
Mid-season	17.45	-7.975	3.925	5804
Summer	27.475	5.9	15.475	6781

Table 3.16 Seasonal averaged temperature and solar radiation data for Caribou, Tas

Abu Dhabi	$T_{max, (^{\circ}C)}$	$T_{min, (^{\circ}C)}$	$T_{av, (^{\circ}C)}$	$S(Wh/m^2)$
Winter	30.65	11.05	20.575	7062
Mid-season	37.975	17.9	27	8070
Summer	44.2	24.025	33.2	8949

Table 3.17 Seasonal averaged temperature and solar radiation data for Abu Dhabi, Tas

Future weather data

The impact of climate change will also be studied by using the future climate data. Future climate is going to change due to the current global carbon dioxide emissions. Modelling climate change is basically predicting the future Greenhouse gas emissions and working out how it influences the climate. But not a single climate file can represent a definitive future. Hence, different climate scenarios are assumed: high emissions, medium emissions and low emissions.

The latest climate projection for the UK is UKCP09 from UK Climate Projections, 2009. The future weather data have a large numbers of associated weather files. UKCP09 are the first climate projections to be probabilistic in nature. Further information can be found at the official website: <http://ukclimateprojections.metoffice.gov.uk/23081#table> and work done by Shamash et al. (2012). UKCP09 have been used for various projects such as flood management, emergency planning. Prometheus (The Use of Probabilistic Climate Change Data to Future-proof Design Decisions in the Building Sector) project from University of Exeter uses UKCP09 to produce weather files for three time periods and 2 emission scenarios in .epw format (Eames et al. 2011).

The climate change world weather file generator CCWorldWeatherGen developed by Sustainable Energy Research Group (University of Southampton) is able to generate climate change weather files for world-wide locations for use in building performance simulation programs (SERG 2013). It uses data from International Panel on Climate Change (IPCC). It is fast to process. It is Microsoft Excel based and transforms 'present-day' EPW weather files into climate change EPW or TMY2 weather files. The underlying methodology is called 'morphing' developed by Belcher et al. (2005). The tool is able to generate weather files for year 2020, 2050 and 2080. All CIBSE's DSY and TSY can be transferred to future climate change weather conditions by using CCWeatherGen for the UK.

London's future climate data is from CIBSE (CIBSE 2013). The future climate data for Abu Dhabi, Hong Kong and Abu Dhabi is obtained by using CCWorldWeatherGen. 2050 medium emissions scenario is used in this study.

3.8.4 Tests programme

Having realized that performance gap is a problem and one of the major causes is the uncertainty in occupancy behavior, most of the current research effort has been put into how to better predict the occupancy behavior and therefore the energy

consumption at the design stage. Some of the studies have suggested assuming a wide range of assumptions on building usage. None of the studies investigated the impact of variation of building usage on facade selection. There can be uncertainties in all parameters and there are many possible occupancy scenarios, so rather than take into account of all of these details, which is time consuming and almost impossible, a scenario which is the most likely to occur should be investigated. In large scale office buildings, it has been found that there is a tendency of over usage of buildings and the actual occupancy hours are longer than assumed.

As discussed in Chapter 2, large offices tend to over-use buildings. Azar and Menassa (2012) found that large offices usually have longer working hours. It varies between 60-80 hours per week whereas in small and medium office buildings it varies between 50-60 hours. AECOM (2012) found that a large proportion of energy was being used during non-working hours. Hence, this work will investigate how the increase of office working hours, i.e. from 10 hours per day to 16 hours per day would influence office facade design, in terms of U-value and g-value, under the selected four climates.

The effect of prolonging working hours from 10 hours to 16 hours will first be studied by the steady-state calculation method. The aim of using this method is to have an understanding of the effect under four climate conditions of London, Hong Kong, Caribou and Abu Dhabi. Dynamic simulation runs then will be carried out in EDSL Tas to study and quantify the effect using more reliable results.

Nowadays, there has been effort to use more energy efficient office equipment and lighting, hence, an internal condition with lower level internal gains will also be studied. It is assumed that the office is occupied with lower occupancy density, lighting and equipment will be more energy efficient, assuming $Q_{occ} = 5W/m^2$, $Q_{lit} = 8W/m^2$, $Q_{eq} = 12W/m^2$. In fact, CIBSE (2015) stated that the heat emission coefficient of LED lighting can be significantly lower than other lighting, which can be as low as 4-5 W/m². Therefore, it is possible to have a low internal heat gain office in practice.

The above mentioned testing conditions are summarised in Table 3.18. Note that it is assumed that the test offices run 7 days a week to enable cross comparison between the steady state calculation method and Tas simulation.

Testing locations: London, Hong Kong, Caribou, Abu Dhabi		
Fixed conditions: ventilation rate:10l/p/s		
WWR 0.7		
U-value ranges: 1.2 – 2.6		
G-value: 0.3, 0.4, 0.5		
Orientations : North, South, East and West.		
Code	Internal conditions	Working schedule
SC1	Normal working hours	0800-1800 (10hrs, 33.7W/m ²)
SC2	Upper-end of internal gains	0700-2300 (16hrs, 33.7 W/m ²)
SC3	Lower-end of internal gains	0800-1800 (10hrs, 25 W/m ²)
SC4	Climate change with normal working hours	0800-1800 (10hrs, 33.7W/m ²)

Table 3.18 Testing occupancy hours

Scenario 1 (SC1) assesses the use of high performance facade in four locations representing four climate types with internal condition of a typical office building usage, which is internal heat gains of 33.7W/m², assuming office operating from 8am to 6pm. Scenario 2 (SC2) investigates the effect of prolonging working hours, from 10 hours a day to 16 hours a day. Scenario 3 (SC3) assesses a situation when there is lower internal heat gains because of the usage of more energy efficient equipment and lighting, and lower level of occupancy density. Scenario 4 (SC4) assesses the impact of potential climate change on facade design in office buildings. Future climate data of London is obtained from CIBSE.

For each location, energy demands for three seasons and the whole year will be calculated using design and weather data summarised in Table 3.10 to Table 3.13. Three levels of g-values are tested, 0.3, 0.4 and 0.5 over U-value with a range from 1.2W/m²K to 2.6 W/m²K.

3.6 Summary

The aim of this project is to investigate the influence of high performance facade on office buildings' energy usage and CO₂ emissions under different climates and internal design conditions. This chapter describes the method that is used and set the testing programme to answer this research question.

There are a number of ways to calculate the energy demand of buildings. It has also been recognized that a plan of checks on calculation quality is needed because of the software involved. A number of steady-state methods and dynamic simulation programs have been reviewed in order to find a method that is fit for purpose for this study. The underlying principle is the heat balance equation.

The most obvious method is using whole building energy prediction tools such as well known building simulation programs like EDSL Tas and Energy Plus. These computer simulation programs aim to model the real, dynamic thermal responses of buildings when subjected to different loads and are accredited. However, the accuracy of results from using a dynamic simulation program largely depend on factors such as if the correct assumptions are made at the initial stages and user proficiency. Hence, a steady-state method adapted from the heat balance equation will also be used to check results from Tas against gross error. Performing preliminary steady-state calculation also has benefits which are 1) to study the influence of major parameters in a fast way and 2) to help to interpret and present large amount of data from dynamic simulation programs. A case study in London was used to validate both methods. Trends from results produced from two different methods are comparable.

Four locations, namely, London, Hong Kong, Caribou and Abu Dhabi representing four climatic conditions are selected. For each location, the influence of high performance facade, in terms of U-values and g-values, on energy demand of perimeter office modules with a typical internal building usage pattern are investigated. North, East, South and West on intermediate floor will be studied. Two extra internal conditions will be tested for each location, which are 1) prolonging working hours, 2) lowering internal gains from occupants, equipment and lighting. These scenarios are very likely to occur in real life and hence are tested. The effect of climate change on facade selection will also be assessed by using further climate data. The next chapter presents the results for London.

CHAPTER 4 INFLUENCE OF HIGH PERFORMANCE FACADES ON ENERGY USAGE IN LONDON OFFICES

Introduction

This chapter investigates the influence of high performance facades, i.e. curtain walls with low U-values, around $1.2\text{W/m}^2\text{K}$ and a low g-value of 0.3, on the energy usage in office buildings in London using the methods described in Chapter 3. Four scenarios are considered, the standard working hour scenario (SC1), prolonged work hours scenario (SC2), lower internal gains scenario (SC3), and scenario 4 (SC4) which assumes the weather conditions predicted for 2050 apply. The test programme is outlined in Table 4.1. For SC1 and SC2, preliminary tests using a steady-state method are carried out alongside the Tas simulation in order to ensure that the results obtained from Tas are reasonable.

Hence, results from the steady-state method are presented first followed by Tas results for SC1 and SC2. For SC3 and SC4, only Tas simulations are performed. In each case, the heating/cooling load is calculated assuming the use of facades with U-values which vary between $1.2\text{W/m}^2\text{K}$ to $2.6\text{W/m}^2\text{K}$ with g-values which vary between 0.3 and 0.5. All tests are carried out on offices facing North, East, South and West.

Fixed conditions:							
Test location: London							
Ventilation rate: 10 liters per person per second (l/p/s)							
WWR = 0.7							
Indoor temperature: 22°C							
Test variables and methods							
Code	U-value ($\text{W/m}^2\text{K}$)	G-value	Orientations	Working schedule	Internal gains (W/m^2)	Weather (CIBSE)	Modelling tools
SC1	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10hrs)	33.7	current	steady state, Tas
SC2	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0700-2300 (16hrs)	33.7	current	steady state, Tas
SC3	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10hrs)	25	current	Tas
SC4	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10hrs)	33.7	Future, 2050	Tas

Table 4.1 Test summary for London

For each scenario, three types of results are presented and discussed: 1) annual results, 2) seasonal energy demand and 3) breakdown values. The annual load results are presented first, and provide trend lines which show the influence of the facade properties, i.e. U and g-values on annual energy performance of offices facing North, South, East or West. In the past, some authors have only looked at facades' energy performance at a certain times of the year, often winter. However, it is more important to get a view of what happens over the course of the year because it helps engineers select the facade which would lead to the lowest annual energy demand. Following this, results showing the effect of U and g-values on the total seasonal energy demand as well as the seasonal heating and cooling loads are presented. Each year is divided into three seasons, namely winter (Jan, Feb, Nov, Dec); mid-season (March, Apr, May, Oct); and summer (June, Jul, Aug, Sept). The results have been broken down into heating and cooling loads. These assist in understanding the trends in the annual graphs. Further insights are provided by presenting the numerical values of principal factors influencing the energy demand. The results are discussed with regard to climate conditions characterised by indoor and outdoor temperature differences and solar irradiance levels. The effect of U-value is discussed followed by g-value. These breakdown values not only help with understanding the influence of individual parameters but also checking if the Tas results are reasonable.

At the end of the chapter, a summary table of the results used to produce the annual graphs is provided in order to quantify the effect of the U and g-values and for ease of comparison. Further tests are also carried out with lower internal heat gains assumption because the level of internal heat gain is found to be important.

4.1 Influence of high performance facade in London offices, SC1

This section presents the test results for London assuming standard working hours scenario (SC1). The test results from the steady-state method are presented and discussed first, followed by the more detailed and accurate results obtained from Tas.

4.1.1 Steady-state study

Climate data

Table 4.2 shows the seasonal average values of outdoor dry-bulb temperature, T_{out} , design indoor temperature, T_{in} , the average temperature difference between indoor and outdoor, ΔT , as well as solar irradiance values for North, South, East and West orientations, S_o . As previously noted, winter covers the period November-February, summer the period between June-September and the remaining months are classed as mid-season. The monthly values are used to calculate the seasonal average temperatures and solar irradiance values.

London	$T_{out}(^{\circ}\text{C})$	$T_{in}(^{\circ}\text{C})$	$\Delta T(^{\circ}\text{C})$	$S_o (W/m^2)$			
				N	E	S	W
Winter	5.8	22	-16.2	14.5	27.1	57.9	27.1
Mid-season	11.0	22	-11.0	49.4	80.8	100.7	80.8
Summer	16.6	22	-5.4	70.4	106.6	111.4	106.6

Table 4.2 London indoor and outdoor temperatures ($^{\circ}\text{C}$), solar irradiance (W/m^2), averaged by seasons

T_{in} = indoor design temperature ($^{\circ}\text{C}$)

T_{out} = outdoor dry-bulb temperature ($^{\circ}\text{C}$)

ΔT = outdoor temperature – indoor temperature ($^{\circ}\text{C}$)

S_o = solar irradiance (W/m^2)

It can be seen that in London, the largest temperature difference occurs in winter which is -16.2°C and that the smallest temperature difference occurs in summer, which is -5.4°C . The average outdoor temperature is always lower than the design indoor temperature as indicated by the negative ΔT values. Additionally, winter months experience the least amount of solar heat gains whereas summer months experience the most. From Table 4.2 it can also be seen that North facing facades experience the lowest solar irradiance whereas South facing facades experience the highest. The solar irradiance values for East and West facing facades are the same.

Annual results

Figure 4.1 (i, ii, iii) shows the effect of U and g-values on annual energy demand (kWh per m² floor area, which applies to the rest of this work) in offices facing North, South, East and West respectively in London under SC1. Figure 4.1(iii) shows the results for both East and West facing offices because they have the same solar irradiance and hence the annual load. It can be seen that lower U-value facades only have an energy saving effect in North facing offices with a g-value of 0.3. In fact, even in this case energy demand does not decrease further once the U-value falls below about 1.8W/m²K. Utilising facades with low U-values increases the annual energy demand in the case of South facing offices with g-values of 0.4 and 0.5, and East and West facing offices with a g-value of 0.5 (Figure 4.1.iii). Lowering the g-value of the facade from 0.5 to 0.3 appears to reduce the annual energy demand in all offices.

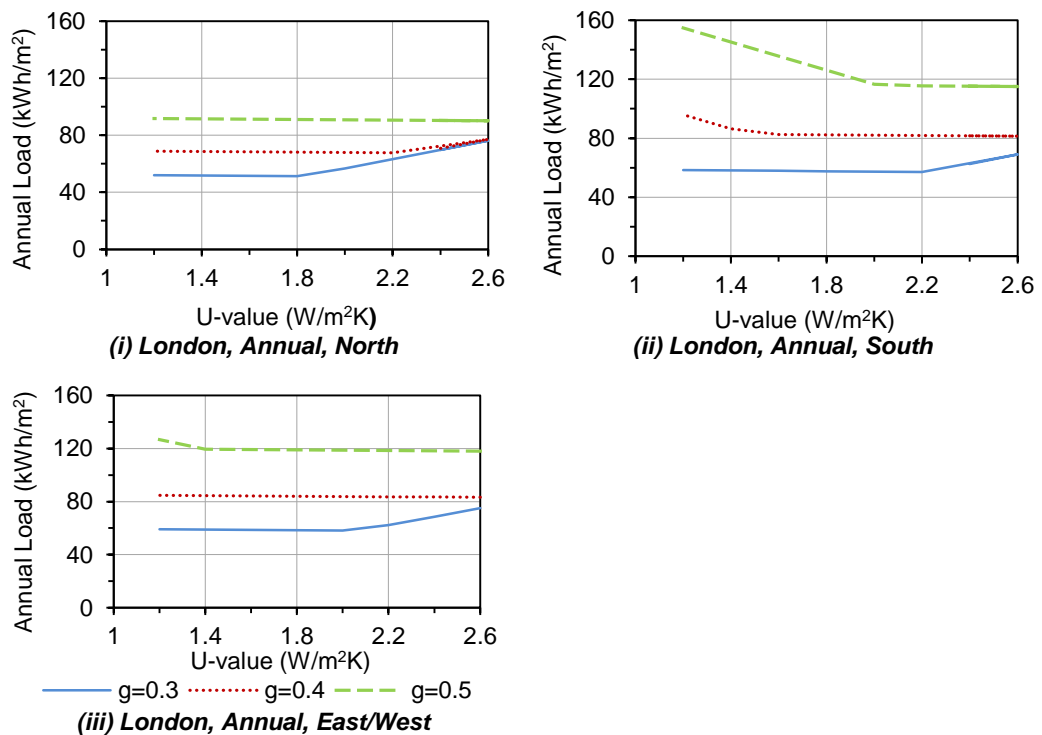


Figure 4.1 Effect of U and g values and building orientation on annual heating/cooling load of test office using steady state calculation, London, SC1

Seasonal results of London, steady state

In order to understand these trends, the seasonal energy demand patterns were investigated. Figure 4.2 to Figure 4.4 show the heating/cooling loads estimated using the steady-state method for London in winter, mid-season and summer respectively. A positive number in the figure indicates there is an overall net heat gain, representing the amount of cooling load. Conversely, a negative number indicates an overall net heat loss, giving the amount of heating load. Both loads are given in kWh/m².

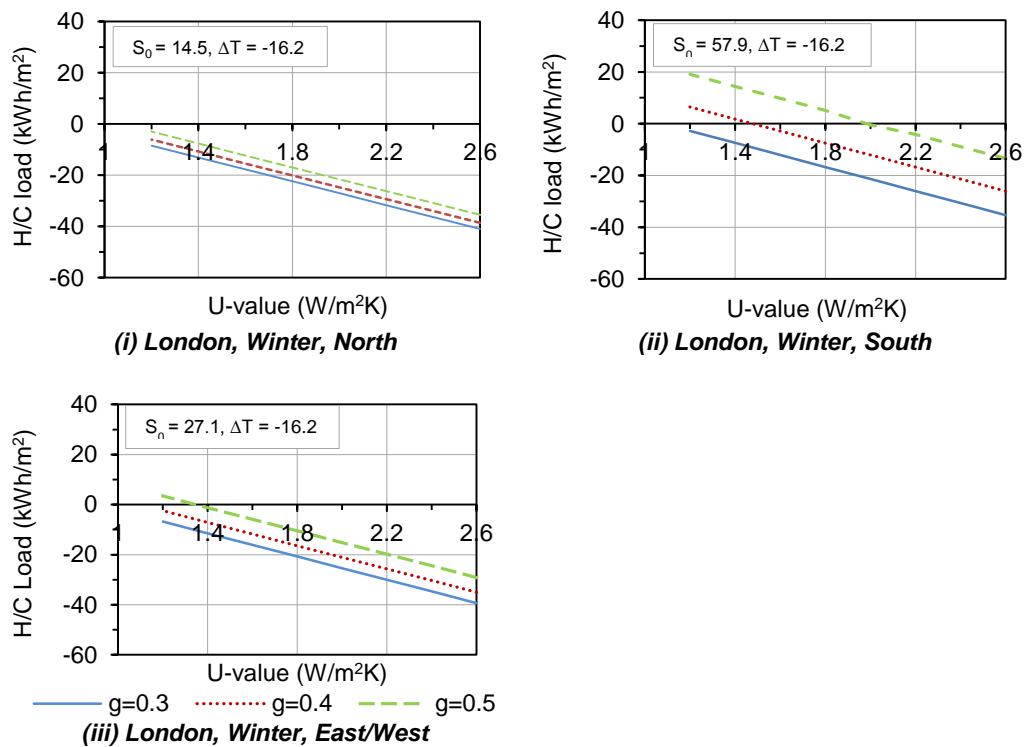


Figure 4.2 Effect of U and g values and building orientation on heating/cooling load of test office using steady state calculation in winter, London, SC1

It can be seen that heating is mostly required in winter for North, East and West facing offices and that lowering the U-value from 2.6W/m²K to 1.2W/m²K reduces the total amount of heat loss and hence the heating demand. For South facing offices (Figure 4.2 ii), it can be seen that in two instances, firstly where $g = 0.5$ and $U = 2\text{W/m}^2\text{K}$, and secondly where $g = 0.4$ and $U = 1.4\text{W/m}^2\text{K}$, the heating load becomes zero. Specifying facades with U-values lower than these critical levels results in a net cooling load. These points were referred to as 'point of inflection' by Masoso and Grobler (2008). In East and West facing offices, the 'point of inflection' occurs at $U = 1.4\text{W/m}^2\text{K}$ when $g = 0.5$ (Figure 4.2 iii).

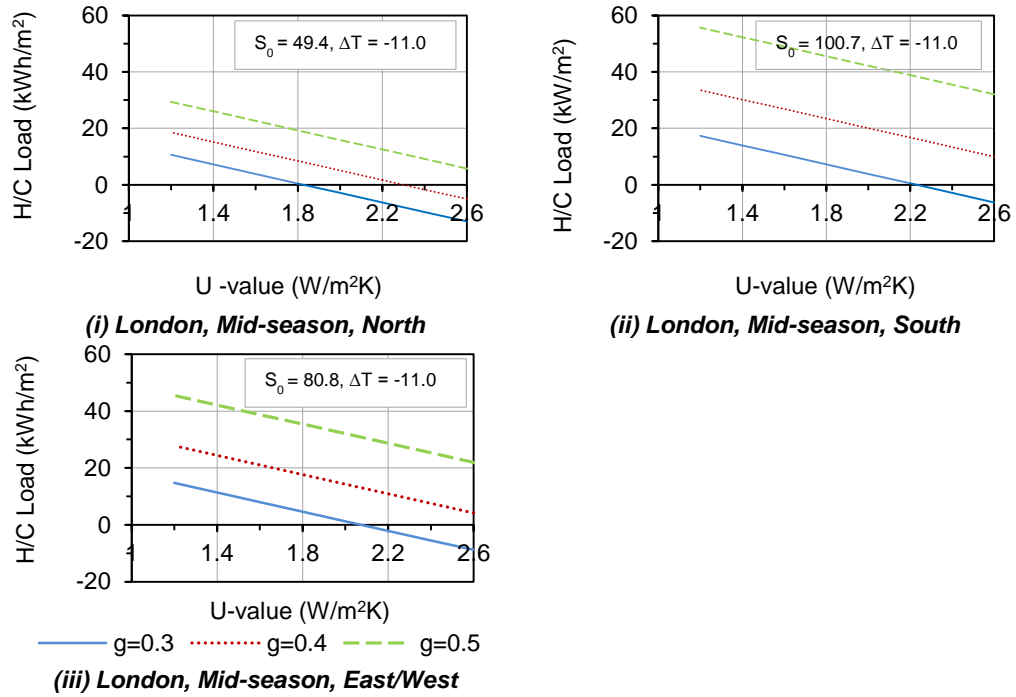


Figure 4.3 Effect of U and g values and building orientation on heating/cooling load of test office using steady state calculation in mid-season, London, SC1

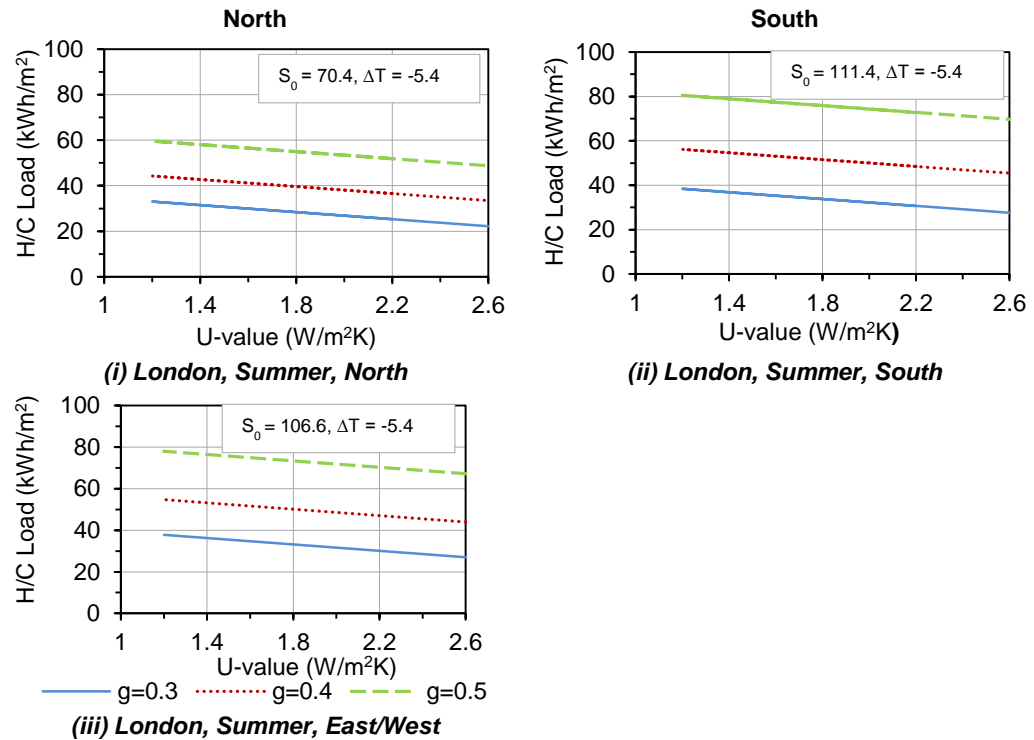


Figure 4.4 Effect of U and g values and building orientation on heating/cooling load of test office using steady state calculation in summer, London, SC1

The effect of lowering the U-value on energy use is worse in mid-season and summer when the weather is warmer and generally there is a higher amount of solar heat gain. During the mid-season months, from Figure 4.3 it can be seen that, irrespective of orientation, cooling is overwhelmingly necessary, with a few points of inflection. For example, when $U=1.8\text{W/m}^2\text{K}$ and $g=0.3$ and when $U=2.3\text{W/m}^2\text{K}$ and $g=0.4$ in North facing offices as well as when $U=2.2\text{W/m}^2\text{K}$ and $g=0.3$ in South, East and West facing offices. Lowering the U-value below these points results in a cooling demand during warmer periods of the year. In summer only a cooling demand exists in all cases and, therefore, lowering the U-value increases cooling load.

The effect of lowering the g-value from 0.5 to 0.3 depends on whether there is an overall heating or cooling requirement. Where there is a heating requirement, for example in North facing offices in winter, facades with higher g-values perform better than those with lower g-values. In summer where there is an overall cooling demand, the opposite is true. Generally, in London, facades with lower g-values have a lower energy demand than those with higher g-values.

Breakdown of the results

Further insights are obtained by considering the values of the principal factors influencing energy demand in Equation 9, namely:

- Conduction heat gain/loss through facade (Q_{cond})
- Ventilation heat gain/loss (Q_{air})
- Internal heat gain (Q_{int})
- Solar heat gain (Q_{sol})

Table 4.3 shows the results for North and South facing offices in winter (W), mid-season (M) and summer (S), assuming $g=0.5$ and the U-value is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. A negative number indicates there is heat loss or a heating demand and vice versa.

	U	North						South			
		Q	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}
W	1.2	-3	-28	-23	41	7	19	-28	-23	41	30
	2.6	-36	-61	-23	41	7	-14	-61	-23	41	30
M	1.2	29	-20	-17	41	25	56	-20	-17	41	52
	2.6	6	-44	-17	41	25	32	-44	-17	41	52
S	1.2	60	-10	-8	41	36	81	-10	-8	41	57
	2.6	49	-20	-8	41	36	70	-20	-8	41	57

Table 4.3 Effect of U-value on energy demand of North and South facing offices in London assuming $g=0.5$, using steady state calculation, SC1

In winter, the average temperature difference between indoors and outdoors, ΔT , is -16.2°C , which is higher than in the two other seasons. Hence, it can be seen from Table 4.3 that conduction heat losses (Q_{cond}) are greatest in winter. In North facing offices using lower U-value facades in winter can reduce this loss and hence lower the overall heating demand from -36kWh/m^2 to -3kWh/m^2 . However, in South facing offices, which receive a higher level of solar heat gain (Q_{sol}), lowering the U-value gives rise to cooling load and increases the overall energy demand from -14kWh/m^2 to 19kWh/m^2 . In general, when there is an overall heating demand, heating loads in South facing offices will be lower than those in North facing offices because of the higher solar heat gains in the former offices.

In mid-season, both heat loss due to conduction and ventilation decrease due to a smaller ΔT , which is -11°C . The amount of solar heat gain increases due to the higher level of solar irradiance present during this period. Lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ reduces the amount of conduction heat loss, but the internal heat gain remains constant and large. These factors result in an overall cooling requirement, which increases with decreasing U-value.

During summer, the average temperature difference between indoors and outdoors is -5.4°C and the level of solar irradiance is at its highest. Hence, the heat losses due to conduction and ventilation are at their lowest, but the amount of solar heat gain is at its highest. Therefore, cooling loads are higher in the summer than the rest of the year. The effect of lowering the U-value remains the same i.e. it reduces conduction heat loss which results in higher cooling loads. However, because ΔT is lower in summer, the effect of lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ on conduction heat loss is less at 10kWh/m^2 , whereas the value is 24kWh/m^2 in mid-season. This is reflected in the gradient of the trend lines shown in Figure 4.3 and Figure 4.4: the gradients of the heating/cooling load curves for summer are less steep than those for mid-season, which means that lowering the U-value has a smaller effect on energy demand. In general, there is a higher cooling demand in South facing offices due to the higher solar heat gain than North facing offices, which is the same as that observed during mid-season.

Table 4.4 shows a similar set of results for North and South facing offices in winter (W), mid-season (M) and summer (S) and assume $U=1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$ but $g=0.3$. In this case, there will be less solar heat gain received through the glass than when $g=0.5$ (Table 4.3) in all three seasons. The resulting effect is that in winter, there is a higher heating demand and no cooling requirement in both the North and South facing offices.

During mid-season, a higher heating demand is observed when $U=2.6 \text{ W/m}^2\text{K}$ but a lower cooling load is observed when $U=1.2\text{W/m}^2\text{K}$. It can be seen that lowering the g-value from 0.5 to 0.3 can reduce unwanted solar heat gain, and hence the total energy required for cooling which is the dominant load in London offices.

	U	North					South				
		Q	Q _{cond}	Q _v	Q _{int}	Q _{sol}	Q	Q _{cond}	Q _v	Q _{int}	Q _{sol}
W	1.2	-9	-28	-23	41	2	-3	-28	-23	41	8
	2.6	-41	-61	-23	41	2	-36	-61	-23	41	8
M	1.2	11	-20	-17	41	7	17	-20	-17	41	13
	2.6	-13	-44	-17	41	7	-6	-44	-17	41	13
S	1.2	33	-10	-8	41	9	39	-10	-8	41	15
	2.6	22	-20	-8	41	9	29	-20	-8	41	15

Table 4.4 Effect of U-value on energy demand of North and South facing offices in London assuming $g=0.3$ using steady-state calculation SC1

Furthermore, when the internal conditions are kept the same, whether lowering the U-value is beneficial depends highly on the external climate conditions, i.e. winter or summer conditions, which are characterised by the average temperature difference between indoor and outdoor temperatures and solar irradiance levels. Having established these trends and first principles, Tas simulation results which are more accurate can be analysed and interpreted in a systematic manner.

4.1.2 SC1 Annual results of London, Tas

This section presents the results from Tas simulations.

Climate data

Table 4.5 shows the seasonal averaged values of hourly weather data used in the Tas simulations. It can be seen that winter is the coldest time of the year with the least amount of solar radiation, whereas summer is the hottest time of the year with the highest amount of solar radiation. The indoor design temperature has been set as 22 °C.

London	T _{max} (°C)	T _{min} (°C)	T _{av} (°C)	Solar radiation (Wh/m ²)
Winter	14.5	0.5	6.8	1489
Mid-season	18.2	1.7	10.5	3780
Summer	25.7	9.3	16.8	5401

Table 4.5 Seasonal averaged temperature and solar radiation data for London, cibse weather file.

T_{max} = maximum outdoor temperature (°C)
 T_{min} = minimum outdoor temperature (°C)
 T_{av} = averaged outdoor temperature (°C)
 S = average total daily solar radiation, averaged by seasons (Wh/m²)

Annual results

Figure 4.5 (i, ii, iii, iv) shows the effect of U and three levels of g-values on annual energy demand (kWh per m² floor area, which applies to the rest of this work) obtained by means of Tas for North, South, East and West facing offices in London respectively. It can be seen that irrespective of office orientation, reducing the U-value of the facade increases annual energy demand. Reducing the U-value from 2.2W/m²K (which is recommended in the UK Building Regulations) to 1.2W/m²K roughly increases the annual energy demand by around 15 %. It can also be seen that lowering the g-value from 0.5 to 0.3 reduces energy demand irrespective of U-value and office orientation. This is most obvious in South facing offices as can be seen in Figure 4.5 (ii).

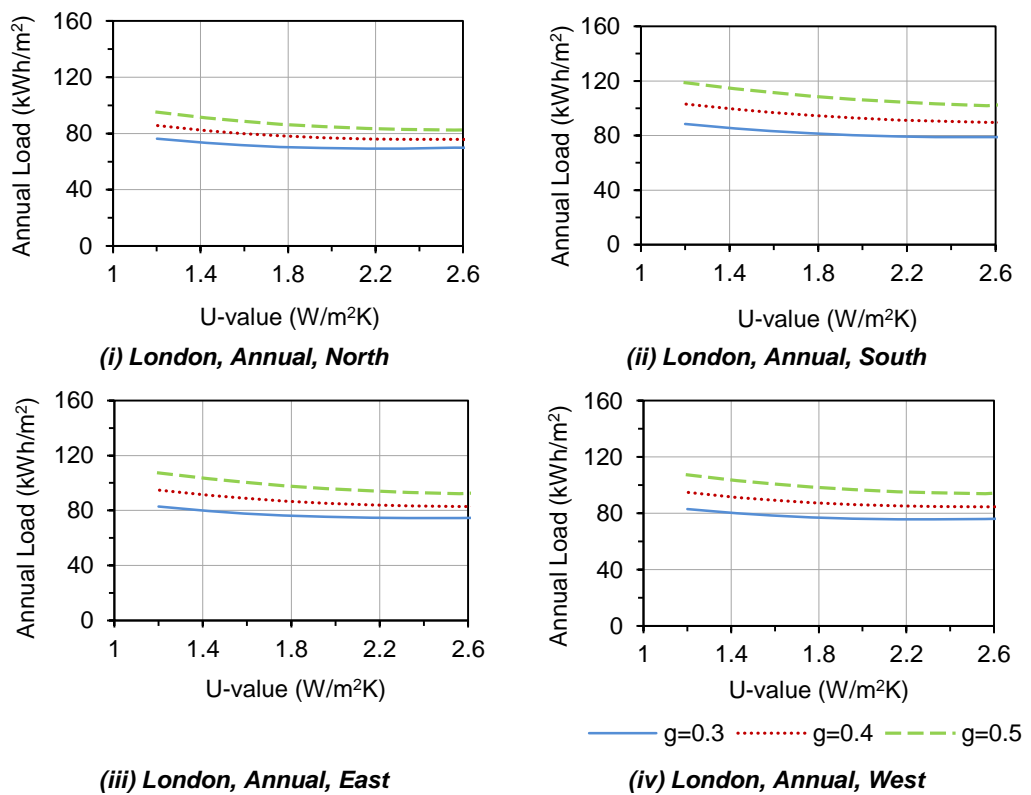


Figure 4.5 Effect of U and g values and building orientation on annual heating/cooling load of test office TAS, London, SC1

4.1.3 SC1 Seasonal results of London, Tas

In order to understand these trends, the energy demand by season was determined. Figure 4.6 to Figure 4.8 show the total energy requirements for offices in winter, mid-season and summer respectively obtained via Tas. Here it can be seen that the effect of lowering the U-value and the g-value of the facade on energy demand varies with season and office orientation. For instance, apart from winter, where it appears the least amount of energy is required when $U=1.6\text{W/m}^2\text{K}$ for North facing offices and around $1.8 - 2\text{W/m}^2\text{K}$ for South, West and East facing offices, in all other cases energy demand increases with decreasing U -value. Lowering the g-value from 0.5 to 0.3 has the greatest effect in reducing energy demand in summer followed by mid-season, in particular in offices that are south facing. In winter, lowering the g-value can reduce energy demand by a small amount in South facing offices, but has almost no effect in offices facing in the other three directions.

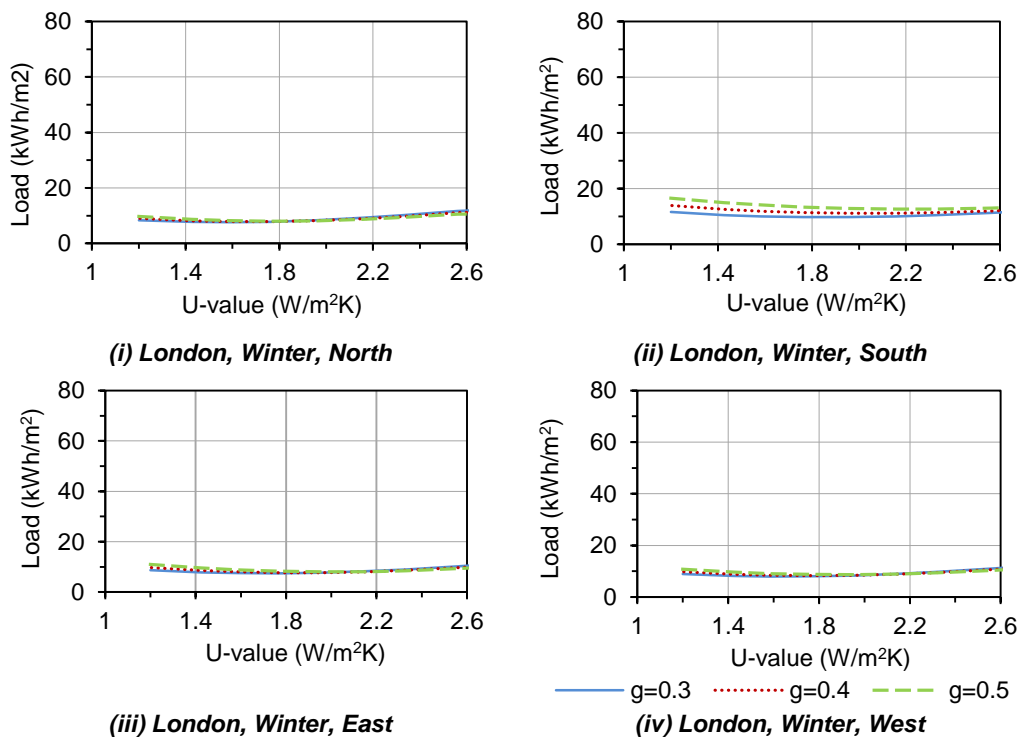


Figure 4.6 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in winter, London, SC1

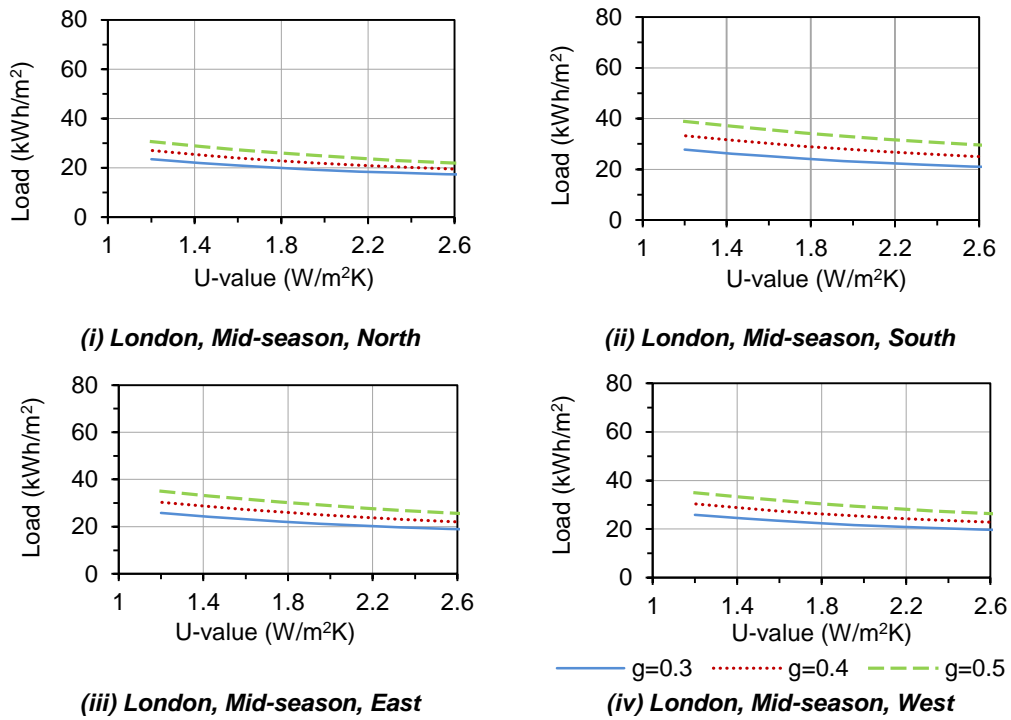


Figure 4.7 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in mid-season, London, SC1

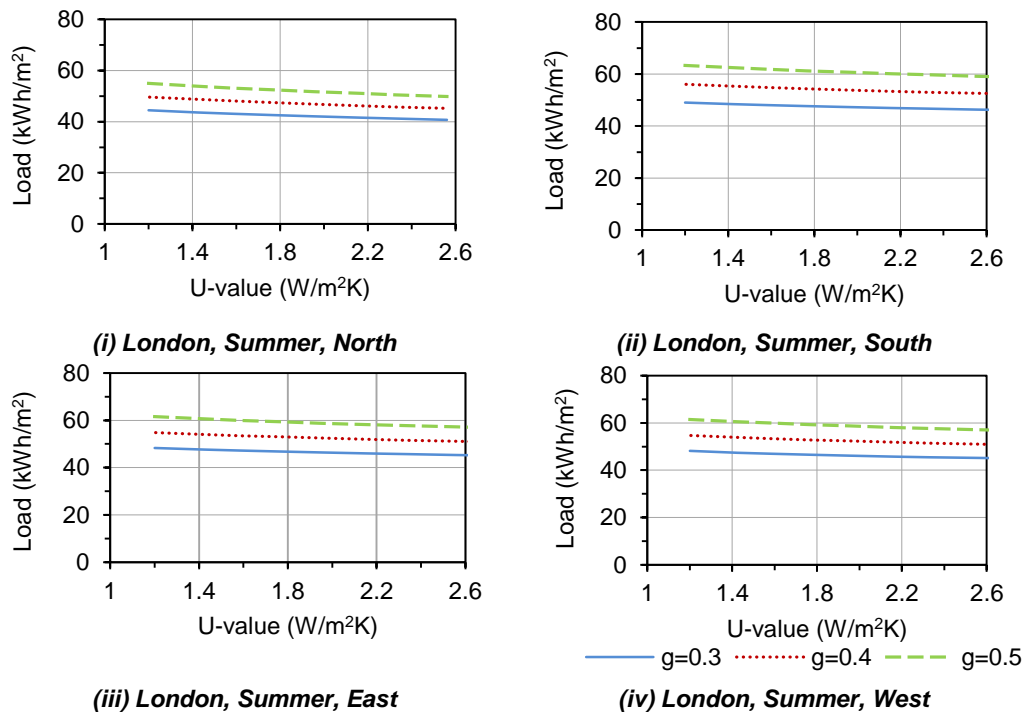


Figure 4.8 Effect of U and g values and building orientation on heating/cooling load of test office TAS in summer, London, SC1

An examination of the nature of seasonal energy usage reveals that offices require a mix of heating and cooling in winter and mid-season. Figure 4.9 and Figure 4.10 show the separate heating and cooling loads which together make up the seasonal total loads in winter (Figure 4.6) and mid-season (Figure 4.7) respectively. In summer, there is only a cooling requirement in all offices. Hence, the summer total loads shown in Figure 4.8 represent the amount of cooling needed in the test offices.

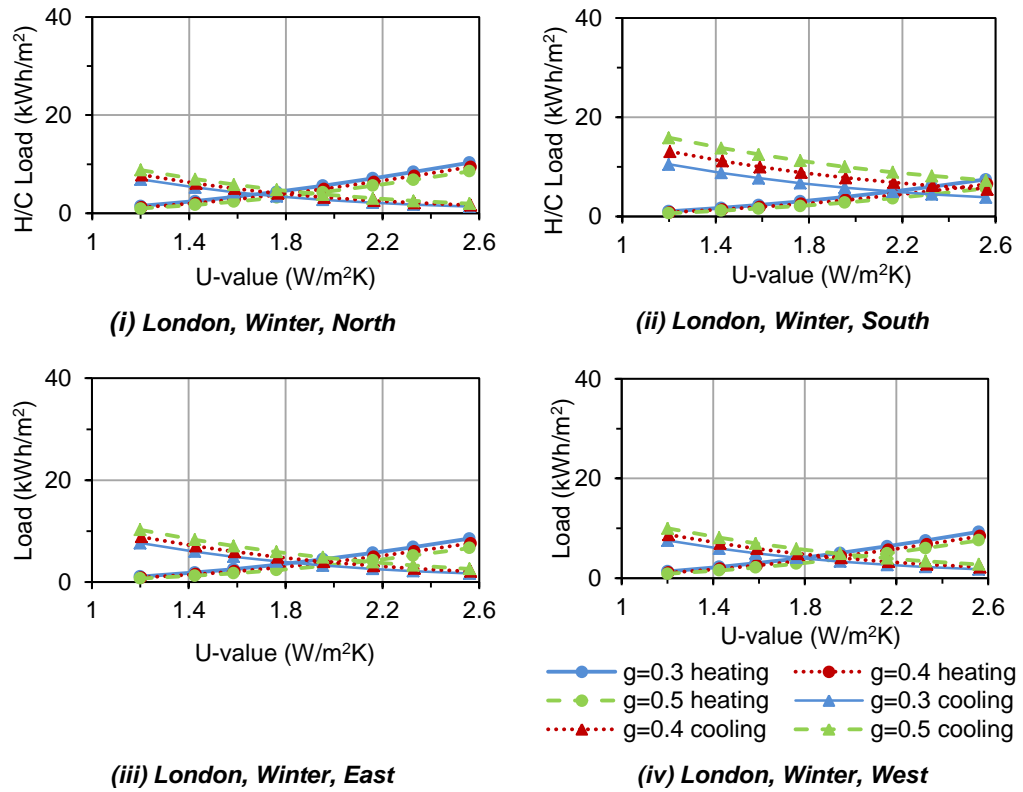


Figure 4.9 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in winter, London, SC1

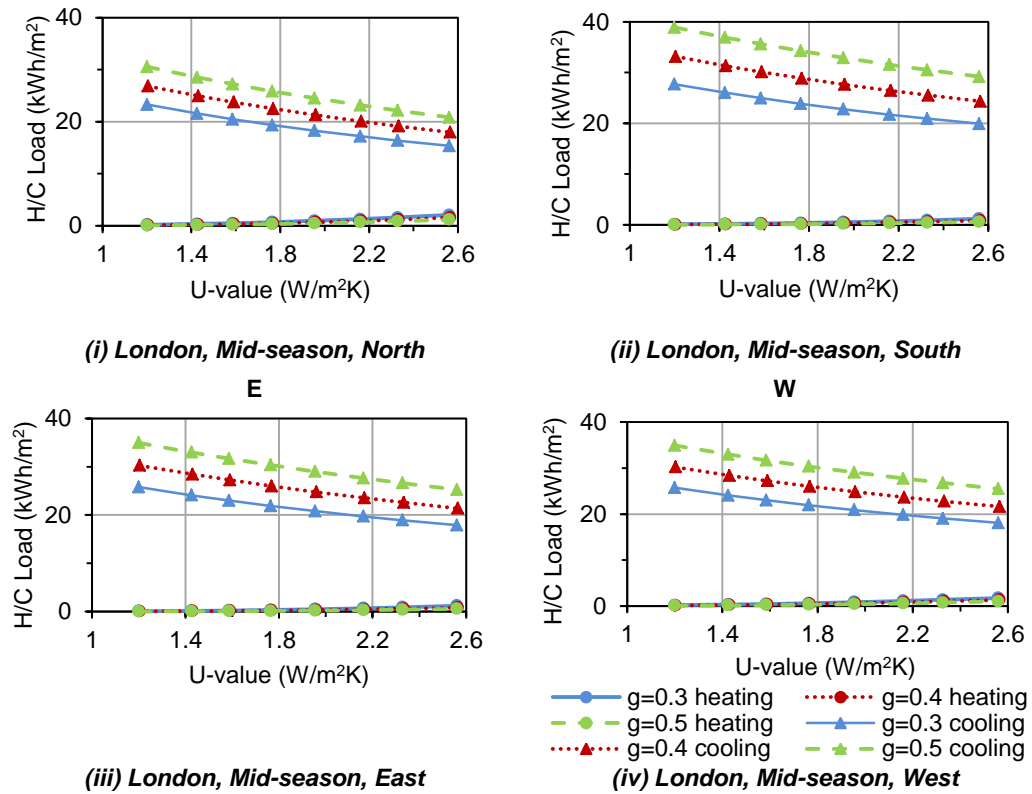


Figure 4.10 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in mid-season, London, SC1

It can be seen from Figure 4.9 that in winter, when the U-value decreases, the heating load also decreases but the cooling load increases. This figure also shows that South facing offices require more cooling than North, East and West facing offices during winter. In mid-season (Figure 4.10), the majority of the energy is required for cooling whereas in summer, there is only a cooling demand. For both the mid-season and summer conditions, lowering the U-value increases the cooling load and hence overall energy demand in all orientations. This is despite the fact that the average outdoor temperatures in London are lower than those indoors throughout the year. Although more cooling is required in summer (Figure 4.8), the trendlines are less steep than those of mid-season (Figure 4.10). This indicates that lower U-value facades perform worse in mid-season. It can also be seen that lowering the g-value can reduce the cooling load and this is more significant in South facing offices.

Breakdown of the results

Further insights are obtained by considering values of the principal factors influencing energy demand, namely:

- Conduction heat gain/loss through facade (Q_{cond} , kWh/m²)
- Ventilation heat gain/loss (Q_{air} , kWh/m²)
- Internal heat gain (Q_{int} , kWh/m²)
- Solar heat gain (Q_{sol} , kWh/m²)
- Heat gain/loss from adjacent spaces due to building heat transfer (Q_b , kWh/m²)

Table 4.6 shows the results for South facing offices in winter (W), mid-season (M) and summer (S) assuming $g = 0.5$ and U is either 1.2W/m²K or 2.6W/m²K. The values for each individual component in the table are the summations of hourly data for each season. Note that Q_h and Q_c represent respectively the heating and cooling load in kWh/m². Q_b measures the heat gain/loss through internal building elements e.g. walls, floors, ceilings and heat temporarily stored in the air (EDSL 2015). It is not discussed here as the values within these results due to the difference it makes is small compared to the other components of the heat balance equation, and additionally, they do not affect overall trends. This is the same in all cases discussed in this chapter.

	U-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	1	16	-24	-20	40	22	-3
	2.6	6	7	-41	-20	40	22	1
M	1.2	0	39	-22	-14	41	37	-3
	2.6	1	29	-35	-14	41	37	-1
S	1.2	0	63	-15	-4	41	44	-3
	2.6	0	59	-21	-4	41	44	-1

Table 4.6 Effect of U-value on energy demand of South facing offices in London assuming $g=0.5$, SC1, Tas

In winter, the averaged outdoor temperature is 6.8°C, which is the lowest of the three seasons considered. Hence, it can be seen in Table 4.6 that generally, the conduction heat losses in winter are the highest in the year. When the U-value is reduced from 2.6 W/m²K to 1.2 W/m²K, the results for winter also show there is an increase in total energy demand of the tested office, as the sum of Q_h and Q_c , increases from 13kWh/m² to 17kWh/m². Although reducing the U-value reduces heat loss due to conduction and hence the heating demand, it also increases the cooling demand resulting in a net increase in energy demand.

In mid-season the averaged outdoor temperature is higher at 10.5°C (Table 5), which reduces the heat loss due to ventilation, Q_{air} , from -20kWh/m² to -14kWh/m². The conduction heat losses are also lower, in the case of facades with a U-value of 2.6W/m²K the conduction heat loss reduces from -41kWh/m² to -35kWh/m². Moreover, because solar irradiation levels are higher during mid-season than in winter, the heat gain from solar irradiation, Q_{sol} , increases from 22kWh/m² to 37kWh/m². The net effect is that more energy is required for cooling despite the fact that the average outdoor temperature is still around 11°C lower than the indoor design temperature.

In summer the outdoor averaged temperature is 16.8°C and therefore the Q_{air} , further reduces to -4kWh/m² and the heat loss due to conduction is also reduced. The sun is stronger during this period which increases irradiation levels. Hence, solar heat gains increase to 44kWh/m², and in turn the overall energy required to regulate office temperatures increases.

From Table 4.6 it can be seen that (excluding the results for winter) if the U-value is 2.6W/m²/K ($Q_h = 6kWh/m^2$) there is generally only a cooling demand. This occurs even though the average outdoor temperatures are lower than those indoors in London throughout the year. From winter, mid-season to summer, the total heat loss due to conduction and ventilation decreases because of the rise in outdoor temperature, and the total heat gains increase because of the rise in solar irradiance level. However, internal heat gain remains at around 40kWh/m² throughout the year and is higher than any other heat transfer terms such as Q_{cond} and Q_{air} . The combined effect of these factors leads to an overwhelming cooling demand throughout the year. Thus, it would seem that under the weather conditions experienced in London the facade traps heat inside the building, and the provision of low U-value facades exacerbates this condition, thereby increasing the energy demand.

The effect of g-value

It appears that g-value has a more pronounced energy saving effect than the U-value. From the results it can be seen that facades with lower g-values have lower energy requirements. From Figure 4.6 to Figure 4.8 it can further be seen that this is true for all office orientations and seasons, with the possible exception of North, East and West facing offices in London, during winter. This is probably due to the fact that these offices generally require heating during winter, whereas cooling is the dominant load at all other times. For example, Figure 4.5 (ii) and Table 4.7 show for South facing offices the effect of g-value on annual energy demand.

	g	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	0.3	1	11	-22	-20	40	12	0
	0.4	1	13	-23	-20	40	17	-1
	0.5	1	16	-24	-20	40	22	-3
M	0.3	0	28	-19	-14	41	19	-1
	0.4	0	33	-21	-14	41	28	-2
	0.5	0	39	-22	-14	41	37	-3
S	0.3	0	49	-10	-4	41	23	0
	0.4	0	56	-12	-4	41	33	-2
	0.5	0	63	-15	-4	41	44	-3

Table 4.7 Effect of g-value on energy demand of South facing offices in London assuming $U=1.2 \text{ W/m}^2\text{K}$, SC1

Here it can be seen that cooling demand reduces with reducing g-value largely because of the associated decrease in solar gains. The results further show that for the assumed condition, using a facade with a g-value of 0.3 instead of 0.5 could result in annual savings of around 30kWh/m^2 . Note that there is a small variation in the values of conduction heat gain which should be constant for a given season irrespective of g-value. The differences might be due to the calculation theory of Tas, however the differences are not large and not discussed here.

Summary

Comparing the results from the Tas simulations with those from the steady-state method shows that the values of energy demand from the two methods are of the same order but more significantly, reducing the U-value often increases energy demand, which is surprising. Although the absolute values of the results from the two methods are different, the overall trends from both methods are essentially the same. The differences in absolute values may be attributable to the different sets of weather data employed and the levels of sophistication of the two calculation methods. Despite the simplicity of the steady-state method, it has been found to be useful to check the output from Tas and make a quick assessment of U and g-value on energy demand.

It can be seen from the results obtained from both calculation methods that cooling is the major load in offices in London. Lowering of facades U-values does not reduce annual energy demand and may actually increase energy demand by limiting heat loss due to conduction.

Throughout the year, the averaged outdoor temperature is lower than the indoor design temperature, and hence, conduction heat loss through the facade always occurs. During winter, which is coldest time of the year, there are high internal gains together with low solar heat gain, which lead to low heating requirements and sometimes even

cooling loads in office buildings. Lower U-value facades trap unwanted heat indoors and hence do not appear to be beneficial in winter. In the summer, there is a higher cooling requirement due to high solar gains and reduced conduction and ventilation losses. Therefore, using lower U-value facades increase cooling demands. In mid-season, the trends are similar to those in summer. Hence, offices using facades with low U-values require more energy than offices operating under similar conditions but using higher U-value facades.

Utilising facades with lower g-values would appear to be a better option for reducing energy demand in offices. This would be most effective in South facing offices, where the solar heat gain is highest. However, lowering the g-value is not good when there is an overall heating demand.

4.2 Effect of prolonged office working hours, SC2

This section presents the results for London assuming a prolonged working hours (SC2). It assumes that the office will be fully occupied for 16 hours per day, 7 days a week, but the remaining conditions, both internal and external are the same as Scenario 1. Results of the steady state analysis are presented first in order to provide a quick understanding of the situation. Comparing with the Tas results, it can be seen that the values of energy demand are of the same order, but more significantly, reducing the U-value increases energy demand.

4.2.1 Steady-state analysis

Figure 4.11 (i, ii, iii) shows the effect of U and g-values on annual energy demand in offices facing North, South, East and West in London respectively. Figure 4.11 (iii) shows the results for both East and West facing offices, as the solar irradiance and hence the annual loads are the same in these test offices. It can be seen that lowering the U-values of the facades increases annual energy demand in all cases. This is most obvious in the case of South facing offices. Furthermore, the effect of lowering the U-value is worse assuming a 16 hour working day rather than a 10 hour working day.

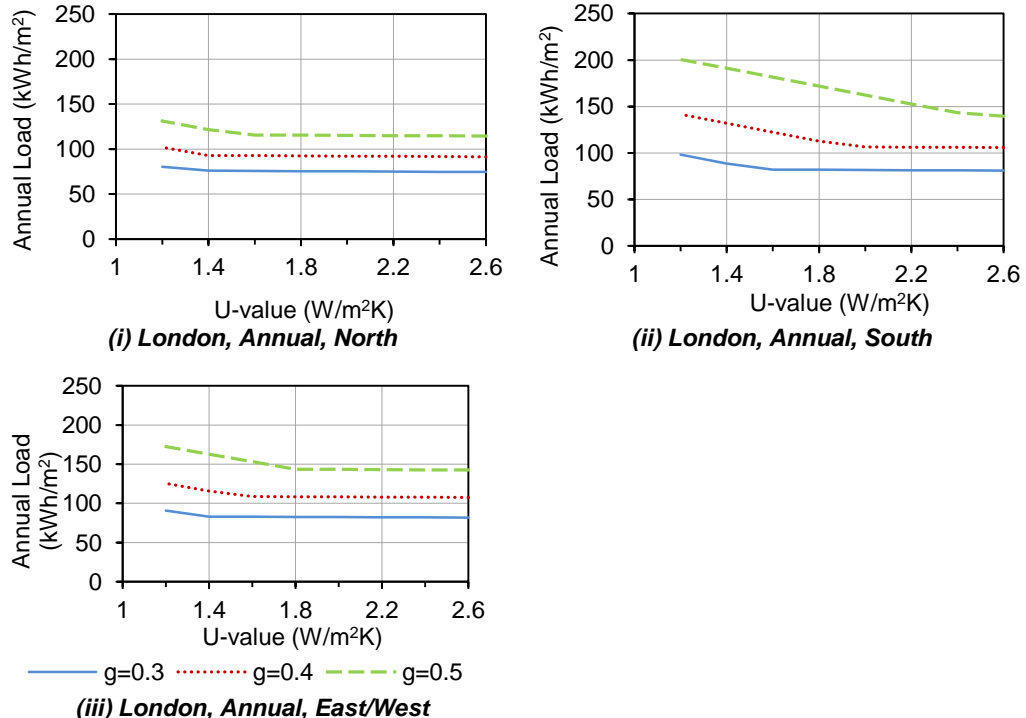


Figure 4.11 Effect of U and g values and building orientation on annual heating/cooling load of test office using steady state calculation, London, SC2

Seasonal results of London, steady state

Seasonal results for winter, mid-season and summer are shown in Figure 4.12, Figure 4.13 and Figure 4.14 respectively. The results for winter (Figure 4.12) show that compared with offices in SC1, there is lower heating demand and higher cooling load in all offices irrespective of orientation. Moreover, there are more points of inflexion and which have shifted towards higher U-values. During mid-season (Figure 4.13), there is now only a cooling requirement in all cases, unlike in SC1 where there was a need for both heating and cooling. In summer (Figure 4.14), the trends are similar, but there is a higher cooling demand. The general trends have been found to be the same: lowering the U-value of the facade increases the cooling load, which is the dominating load in offices in London.

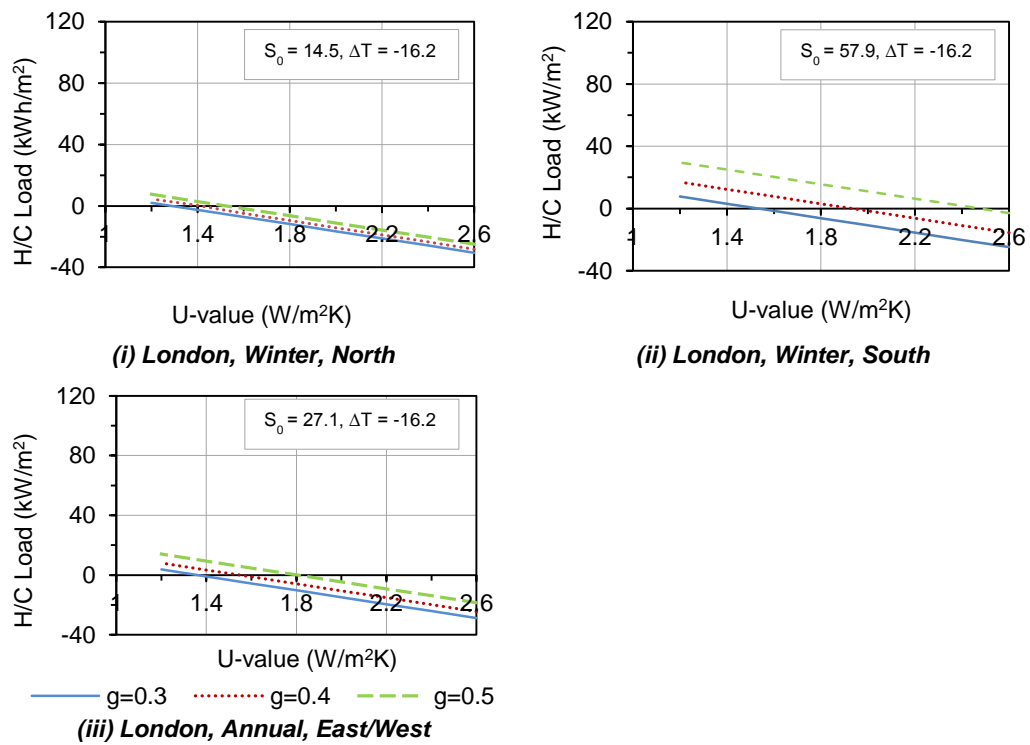


Figure 4.12 Effect of U and g values and building orientation on heating/cooling load of test office using steady state calculation in winter, London

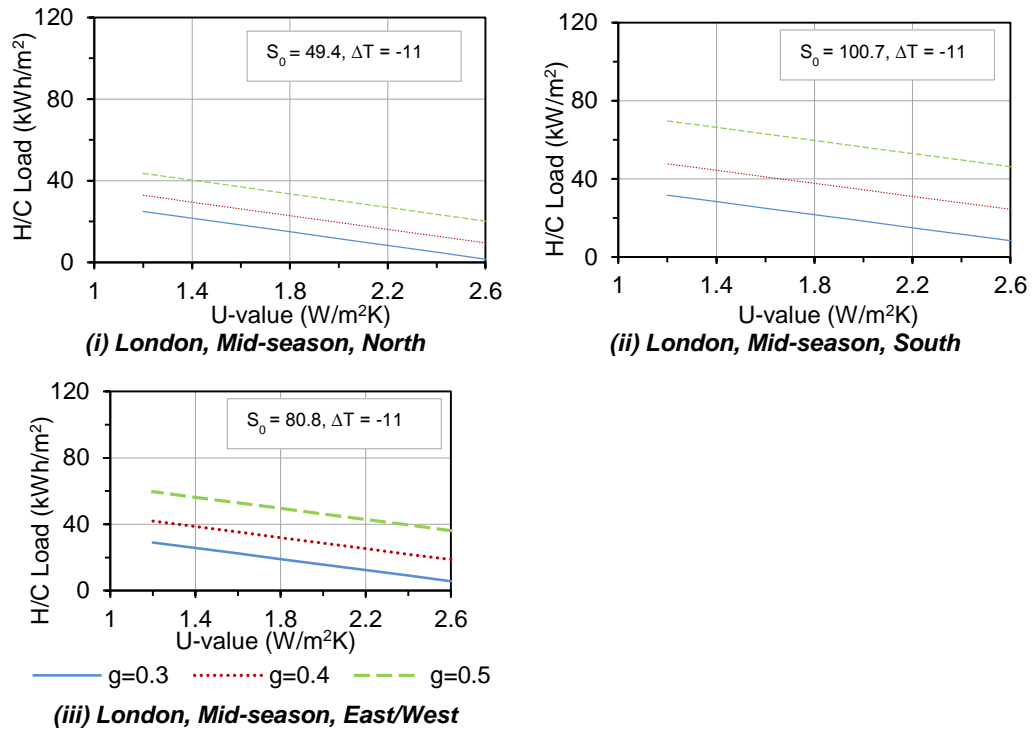


Figure 4.13 Effect of U and g values and building orientation on heating/cooling load of test office using steady state calculation in mid-season, London

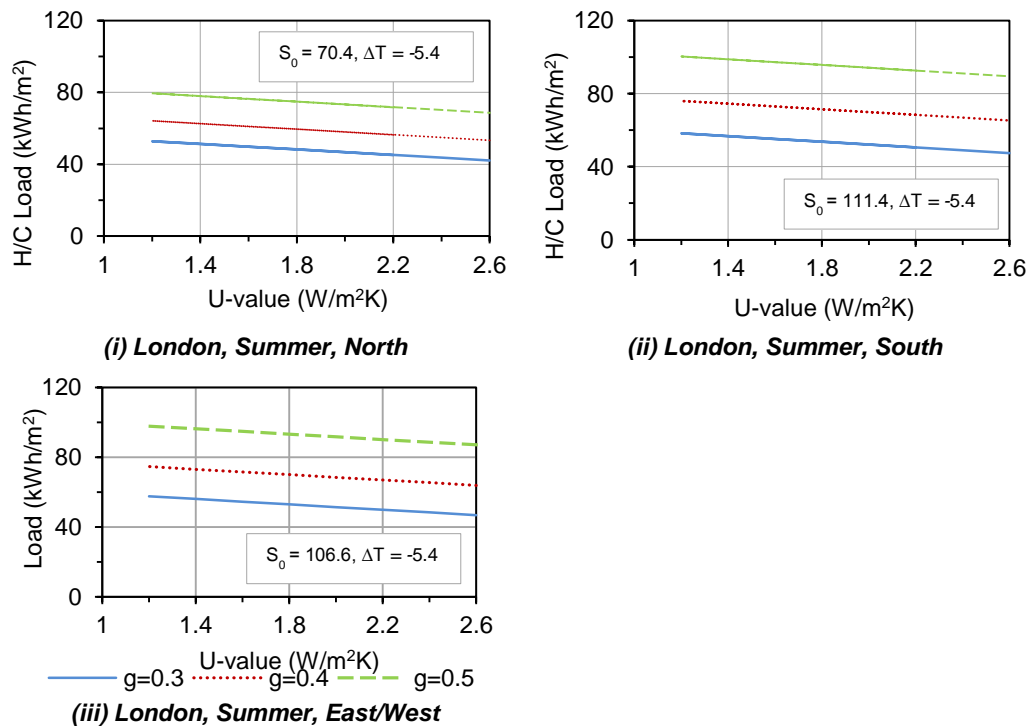


Figure 4.14 Effect of U and g values and building orientation on heating/cooling load of test office using steady state calculation in summer, London

These results can be further explained by looking at individual terms used to calculate heating and cooling. Table 4.8 show the effect of lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ on the values of the principal terms in the heat balance equation for each season in North and South facing offices assuming $g=0.3$. Table 4.9 shows these values when $g=0.5$. It can be seen that the internal heat gain has risen from 41kWh/m^2 to 66kWh/m^2 due to the longer working hours. The heat loss due to conduction, however, remains the same but there is an increase in ventilation heat loss. The overall effect is that there is higher cooling requirement in all seasons. Lowering the g-value of the facade from 0.5 to 0.3 reduces the cooling load and hence the annual energy loads in offices.

		North					South				
	U	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}
W	1.2	2	-28	-37	66	2	8	-28	-37	66	8
	2.6	-31	-61	-37	66	2	-25	-61	-37	66	8
M	1.2	25	-20	-27	66	7	32	-20	-27	66	13
	2.6	2	-44	-27	66	7	8	-44	-27	66	13
S	1.2	53	-9	-12	66	9	59	-9	-12	66	15
	2.6	42	-20	-12	66	9	48	-20	-12	66	15

Table 4.8 Effect of U-value on energy demand of North and South facing offices in London assuming $g=0.3$, SC2

		North					South				
	U	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}
W	1.2	8	-28	-37	66	7	30	-28	-37	66	30
	2.6	-25	-61	-37	66	7	-3	-61	-37	66	30
M	1.2	44	-20	-27	66	25	70	-20	-27	66	52
	2.6	20	-44	-27	66	25	47	-44	-27	66	52
S	1.2	80	-9	-12	66	36	101	-9	-12	66	57
	2.6	69	-20	-12	66	36	90	-20	-12	66	57

Table 4.9 Effect of U-value on energy demand of North and South facing offices in London assuming $g=0.5$, SC2

4.2.2 Annual results for London, Tas

Figure 4.15 (i, ii, iii, iv) show the effect of U-value and g-value on annual load obtained from Tas for offices facing North, South, East and West, respectively. This assumes the offices are occupied for 16 hours per day, from 7am to 11pm rather than 10 hours from 8am to 6pm as was the case in Scenario 1. It can be seen that like Scenario 1 decreasing the facade's U-value would increase annual load in all offices irrespective of orientation. It can also be seen that lowering the g-value from 0.5 to 0.3 can reduce energy demand irrespective of U-value and office orientation but the impact of this change is the largest in South facing offices. In general, the annual loads found in SC2 are higher than those in SC1 due to the longer building operating hours, as are the seasonal loads which are discussed next.

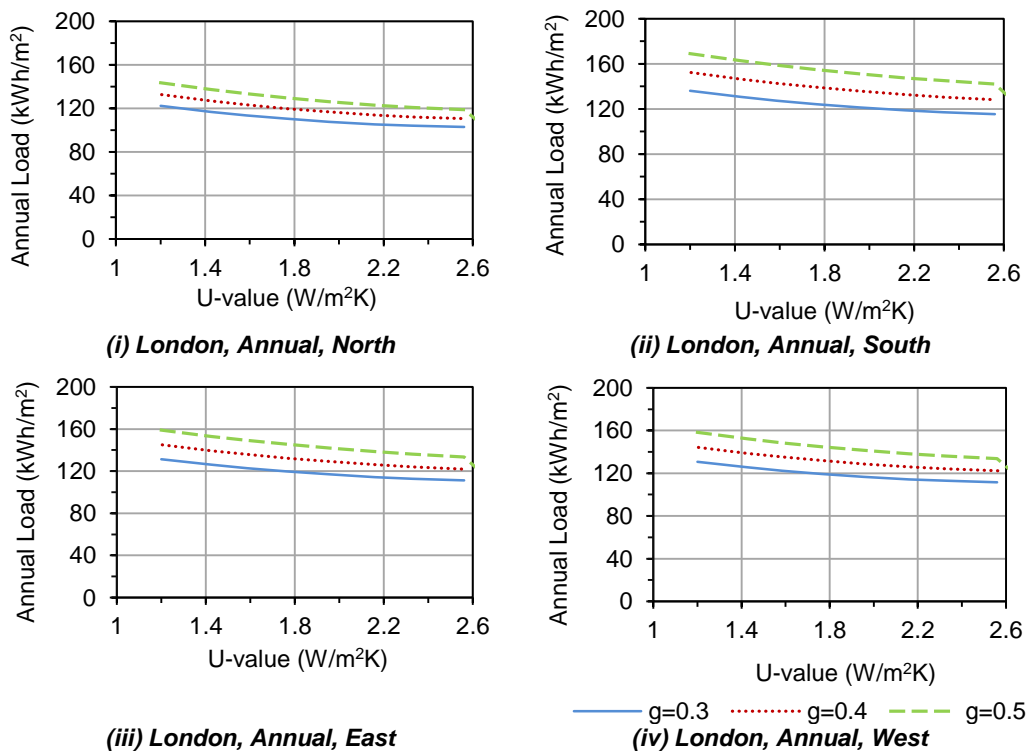


Figure 4.15 Effect of U and g values and building orientation on annual heating/cooling load of test office TAS, London, SC2

4.4.3 SC2 Seasonal results for London, Tas

The seasonal total energy loads for winter, mid-season and summer are shown in Figure 4.16, Figure 4.17 and Figure 4.18 respectively. It can be seen from Figure 4.16 that in winter, the least amount of energy is required when the facade's U-value is around 2.2 - 2.4 W/m²K in all cases, apart from South facing offices where the load continuously increases with decreasing U-value. In mid-season (Figure 4.17) and summer (Figure 4.18), it is more obvious that the energy demand increases with decreasing U-value irrespective of office orientation.

The effect of lowering the g-value on seasonal energy demand can also be seen in these figures. In winter, lowering the g-value from 0.5 to 0.3 can reduce the energy demand in South facing offices, however, it has little effect on offices facing other directions. Lowering the g-value reduces energy demand in all cases during mid-season and summer.

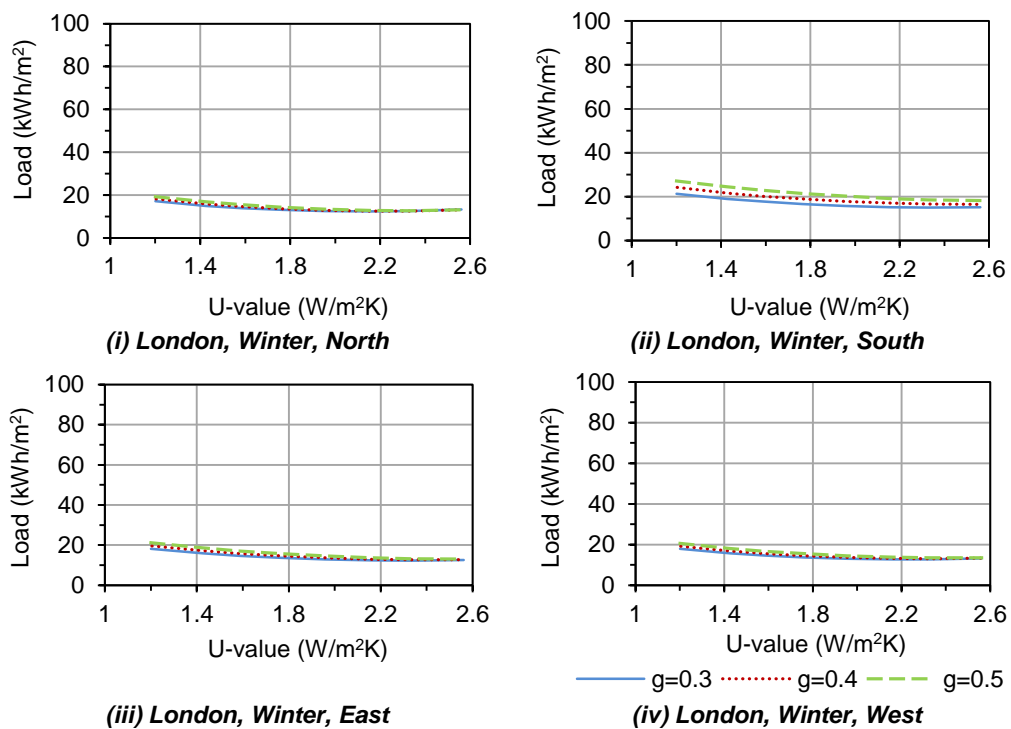


Figure 4.16 Effect of U and g values and building orientation on total load of test office using TAS, winter, London, SC2

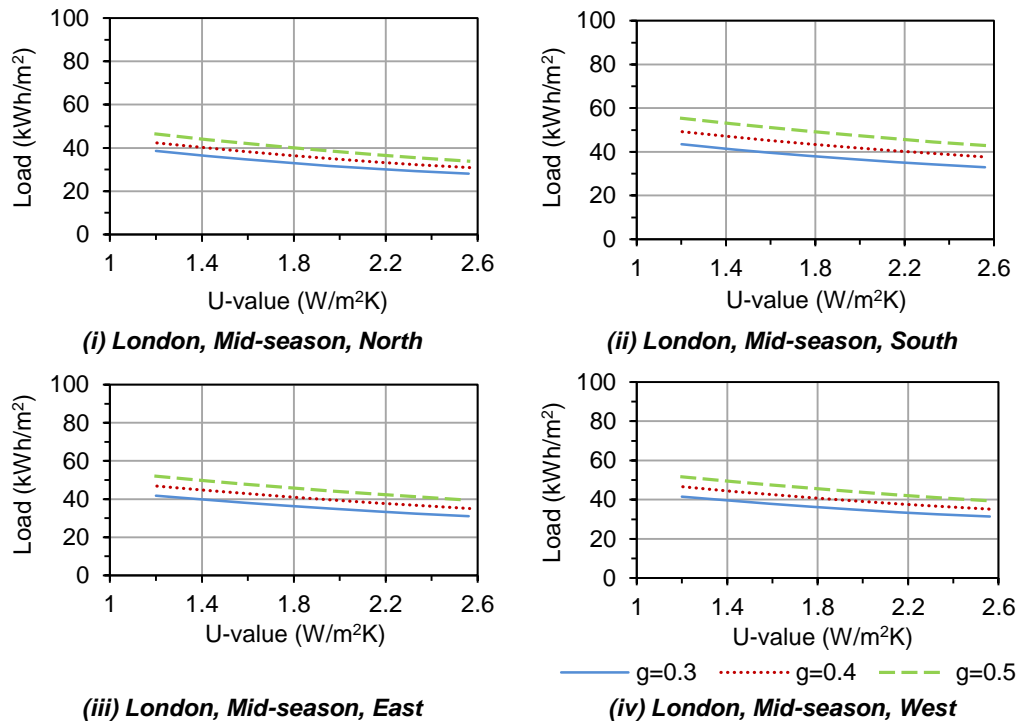


Figure 4.17 Effect of U and g values and building orientation on total load of test office using TAS in mid-season, London, SC2

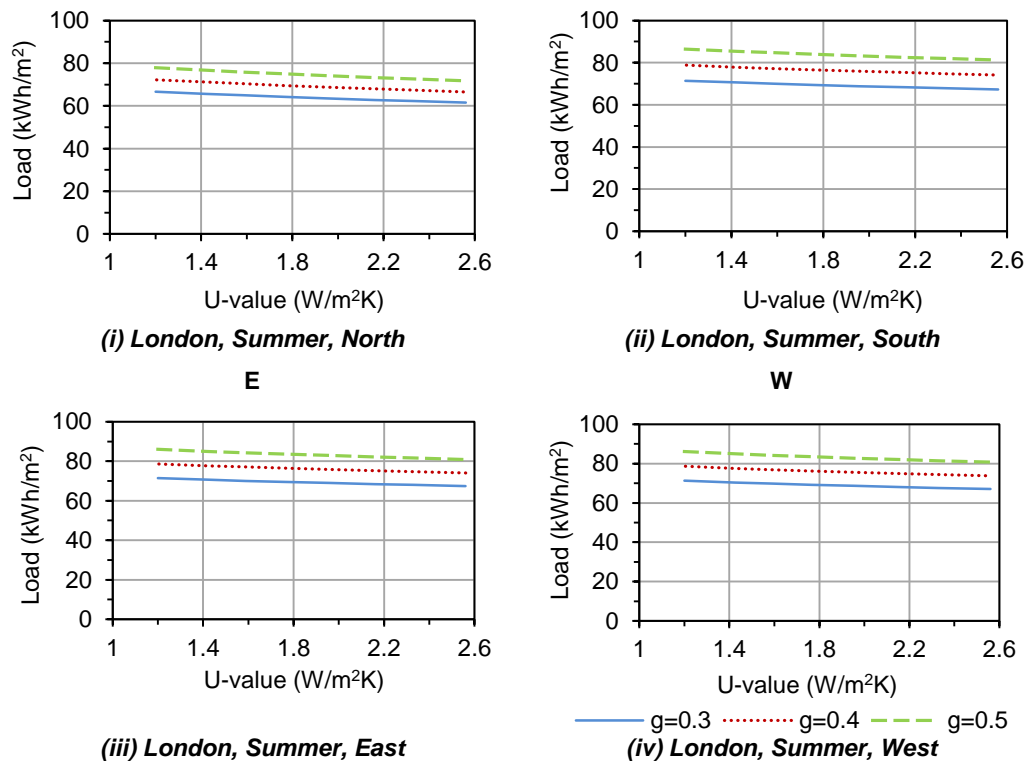


Figure 4.18 Effect of U and g values and building orientation on total load of test office TAS in summer, London, SC2

The nature of the energy demand was also assessed using Tas as shown in Figure 4.19 and Figure 4.20. In winter (Figure 4.19), offices require a mix of heating and cooling. Decreasing the U-value of the facade can cause the heating demand to decrease and the cooling demand to increase. Comparing with results of the 10 working-hour scenario (SC1) shown in Figure 4.9 it can be seen that there is a lower heating requirement and a higher cooling demand in offices operated for longer working hours. Moreover, the point at which the heating and cooling lines intersect (i.e. inflection point) occurs at higher U-values compared with the results for SC1. In mid-season (Figure 4.20), there is minimal heating demand, and in summer there is no heating demand. In all cases, the cooling load increases with decreasing U-value. Overall, there is a larger cooling load for a given office in SC2 than SC1.

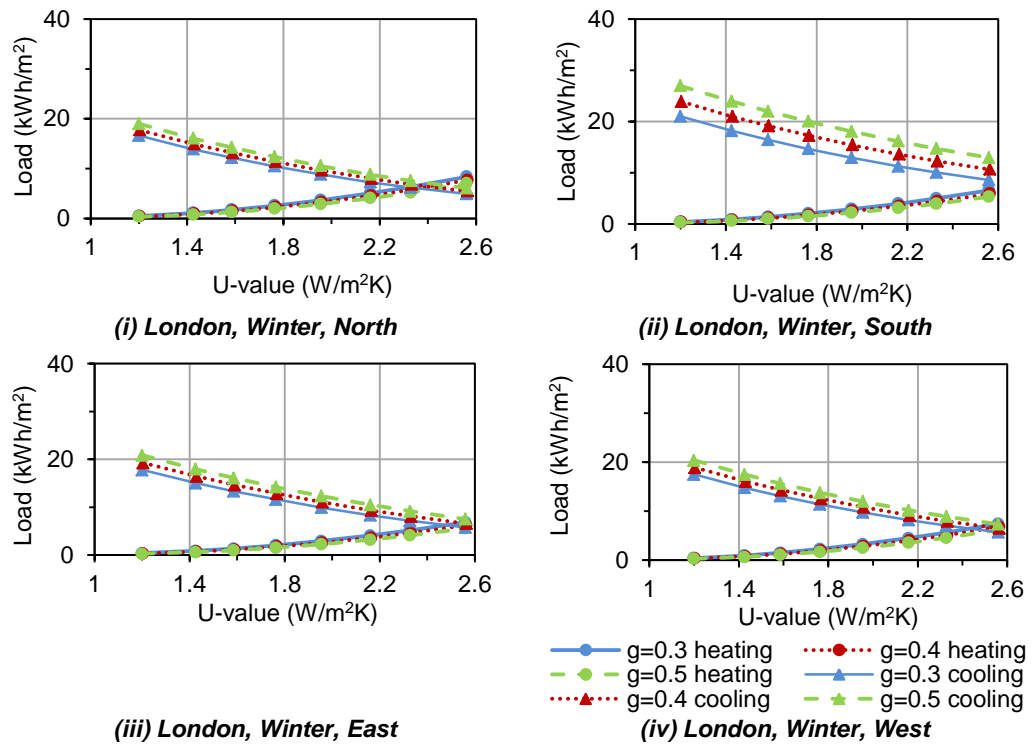


Figure 4.19 Effect of U and g values and building orientation on heating/cooling load of test office using Tas in winter, London, SC2

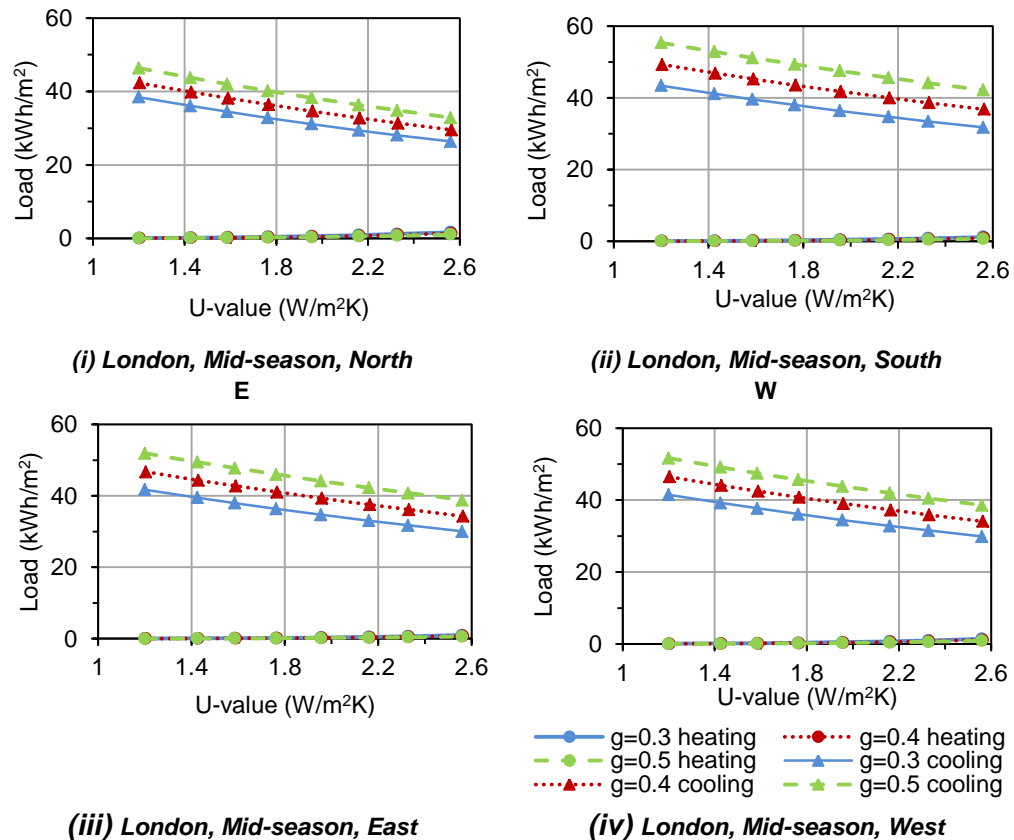


Figure 4.20 Effect of U and g values and building orientation on heating/cooling load of test office using Tas, mid-season, London, SC2

Breakdown of the results

Further insights have been obtained by considering values of the principal factors influencing energy demand. Table 4.10 shows the results for South facing offices in winter (W), mid-season (M) and summer (S) assuming $g = 0.5$ and the U-value is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. The values in the table are the summation of the hourly energy demand of individual terms for each season. Comparing with Table 4.6, it can be seen that longer working hours resulted in a small increase in the total amount of conduction heat loss and higher ventilation heat loss in all three seasons. The internal heat gains for each season rose from around 40kWh/m^2 to around 65kWh/m^2 due to the longer working hours, however, solar heat gains remained the same. Overall, longer working hours resulted in higher cooling demands in all three seasons. The demand for heating in winter, mid-season and summer remained almost the same in SC2 when compared with SC1. But lowering the U-value lead to higher cooling loads in the offices because it unfavourably reduces conduction heat loss.

	U	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	1.2	0	27	-27	-33	65	22	0
	2.6	5	13	-48	-33	65	22	2
M	1.2	0	55	-23	-24	66	37	-1
	2.6	1	42	-39	-24	66	37	1
S	1.2	0	86	-14	-8	66	44	-1
	2.6	0	81	-21	-8	66	44	0

Table 4.10 Effect of U-value on energy demand of South facing offices in London assuming g=0.5, SC2

Looking at annual performance, the effect of lowering the U-value becomes larger when working hours are increased from 10 to 16 hours. For example, when g=0.5, total energy demand increased by 26kWh/m² in SC2 whereas it increased by 17kWh/m² for SC1 when the U-value of the facade was lowered from 2.6W/m²K to 1.2W/m²K.

Effect of g-value

	g	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	0.3	0	21	-25	-33	65	12	2
	0.4	0	24	-26	-33	65	17	1
	0.5	0	27	-27	-33	65	22	0
M	0.3	0	43	-20	-24	66	19	1
	0.4	0	49	-22	-24	66	28	0
	0.5	0	55	-23	-24	66	37	-1
S	0.3	0	71	-10	-8	66	23	1
	0.4	0	79	-12	-8	66	33	0
	0.5	0	86	-14	-8	66	44	-1

Table 4.11 Effect of g-value on energy demand of South facing offices in London assuming U=1.2 W/m²K, SC2

Table 4.11 shows the effect of g-value on seasonal energy demand for South facing offices. Like SC1, the results show that lowering the g-value reduces energy demand in all seasons. The cooling load reduces with reducing g-value. These reductions are comparable to those obtained for scenario 1 (Table 4.7). This is because lowering the g-value only influences solar heat gain, which remains the same in SC1 and SC2. The extra working hours in SC2 occur either early in the morning or in the evening when there are very little solar heat gains.

Summary

Analysis of both the annual and seasonal Tas results show the general trends observed in SC2 are similar to those in SC1. Cooling is the major load in offices in London. Lowering the U-value in offices in London with extended working hours increases the annual energy demand by limiting the heat loss due to conduction. However, lowering the g-value is beneficial because it can reduce unwanted solar heat gain. The energy reduction potential of low g-value facades is the largest in South facing offices which experience the highest amount of solar heat gain. However, lowering the g-value is not good at times when there is an overall heating demand.

Extending working hours from 8am to 6pm (10 working hours a day) to 7am to 11pm (16 working hours a day) increased energy demand both seasonally and annually. In winter, comparing Figure 4.9 with Figure 4.19, the amount of heating required in SC2 is the same as that in SC1, but the cooling load increased. The cooling requirement in both mid-season and summer has also increased in SC2. Hence, even though the extended hours occur in the early morning and late evening when there is little solar radiation, cooling is still required during those hours because of heat gains from equipment, people and lighting. Hence, lower U-value facades still perform poorly in this situation because they trap unwanted heat inside office buildings.

4.3 Effect of lowering internal gain, SC3

This section presents results for London assuming internal gains of 25W/m^2 rather than 33.7W/m^2 but a standard working schedule consisting of 10 working hours per day, 7 days a week. Only the results from the Tas simulations are presented here.

4.3.1 Annual results, Tas

Figure 4.21 (i, ii, iii, iv) shows the effect of U and g-values on annual energy demand obtained by means of Tas for North, South, East and West facing offices respectively. It can be seen that the effect of utilising facades with low U-values depends on both office orientation and g-values. Thus, in the cases of facades with $g=0.3$, lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ reduces the annual energy demand irrespective of office orientation. This effect is less pronounced when $g=0.4$, and in North facing offices when $g=0.5$. Lowering the U-value has little effect in the cases of East or West facing offices with $g=0.5$, but in the cases of South facing offices with $g=0.5$, there is a small increase in the annual energy demand. Comparing the results from SC1, the annual loads in SC3 are found to be I.

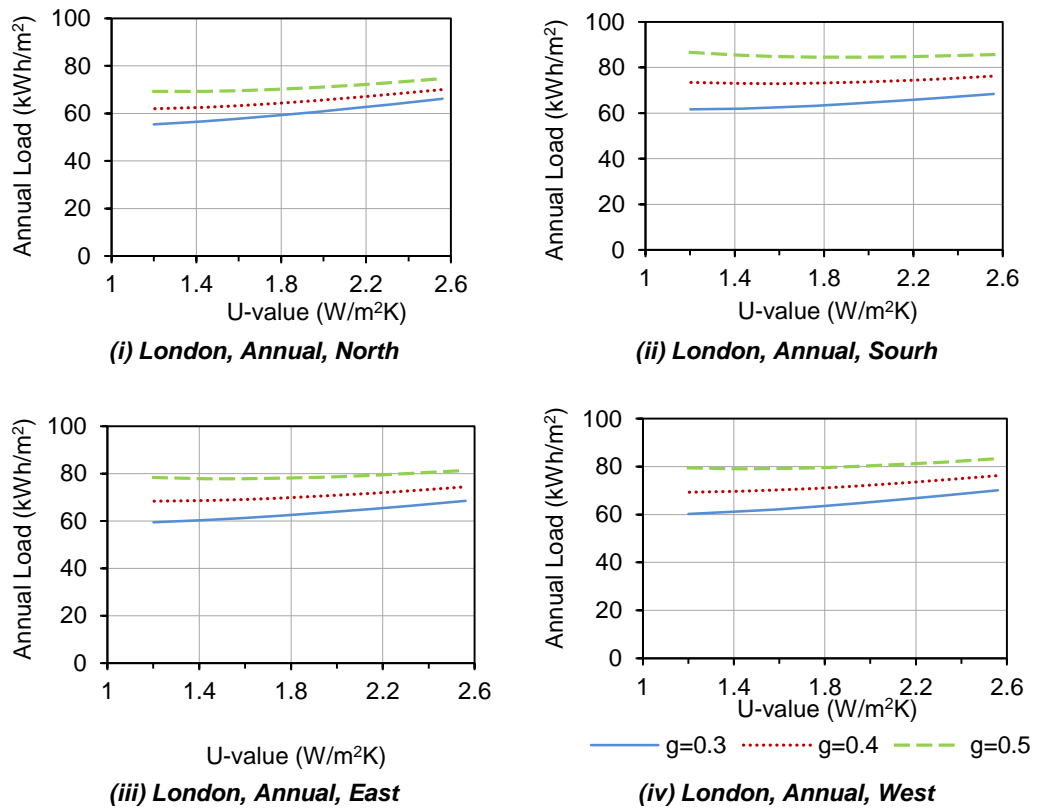


Figure 4.21 Effect of U and g values and building orientation on annual heating/cooling load of test office TAS, London, SC3

4.3.2 Seasonal trends, Tas

In order to understand these trends, the energy demand by season was determined. Figure 4.22, Figure 4.23 and Figure 4.24 show the total heating and cooling loads obtained via Tas in winter, mid-season and summer respectively. Here it can be seen that in winter, lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ can reduce the energy demand from around 20kWh/m^2 to 10kWh/m^2 in all offices irrespective of orientation or g-value. Lowering the g-value has little effect in winter. During mid-season, lowering the U-value does not appear to have much effect when $g=0.3$, but can increase the energy demand when $g=0.4$ and 0.5 . This is most obvious when $g=0.5$. In summer, lowering the U-value increases the energy demand irrespective of orientation. Lowering the g-value is beneficial in both mid-season and summer.

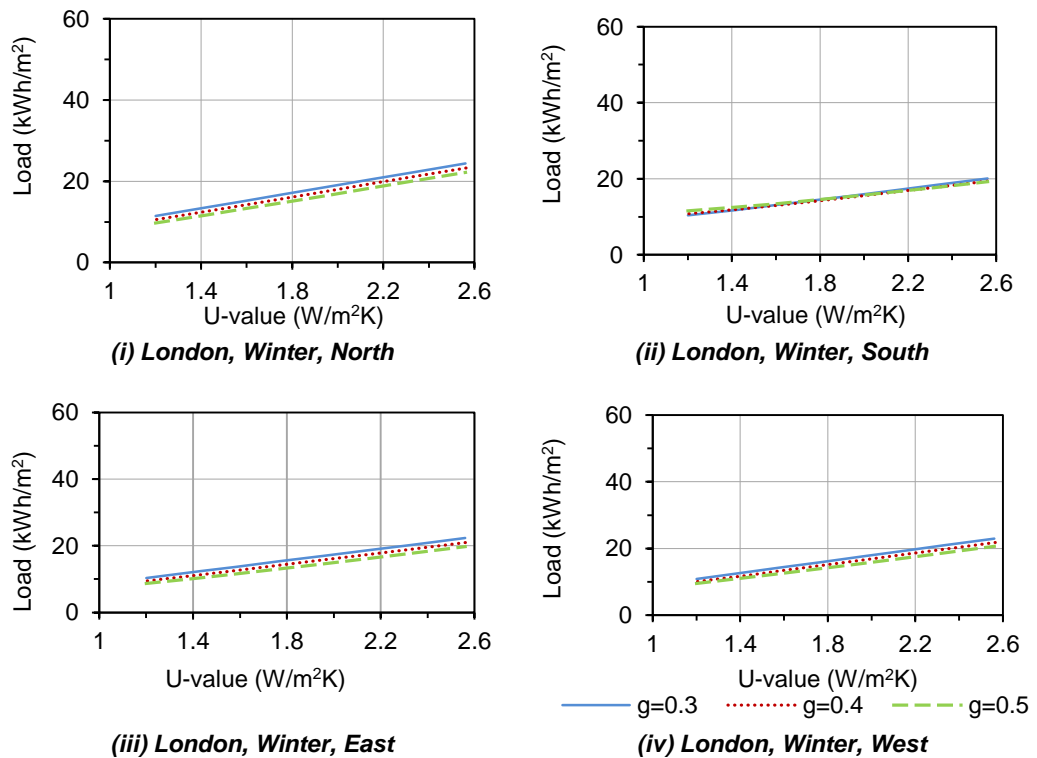


Figure 4.22 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in winter, London, SC3

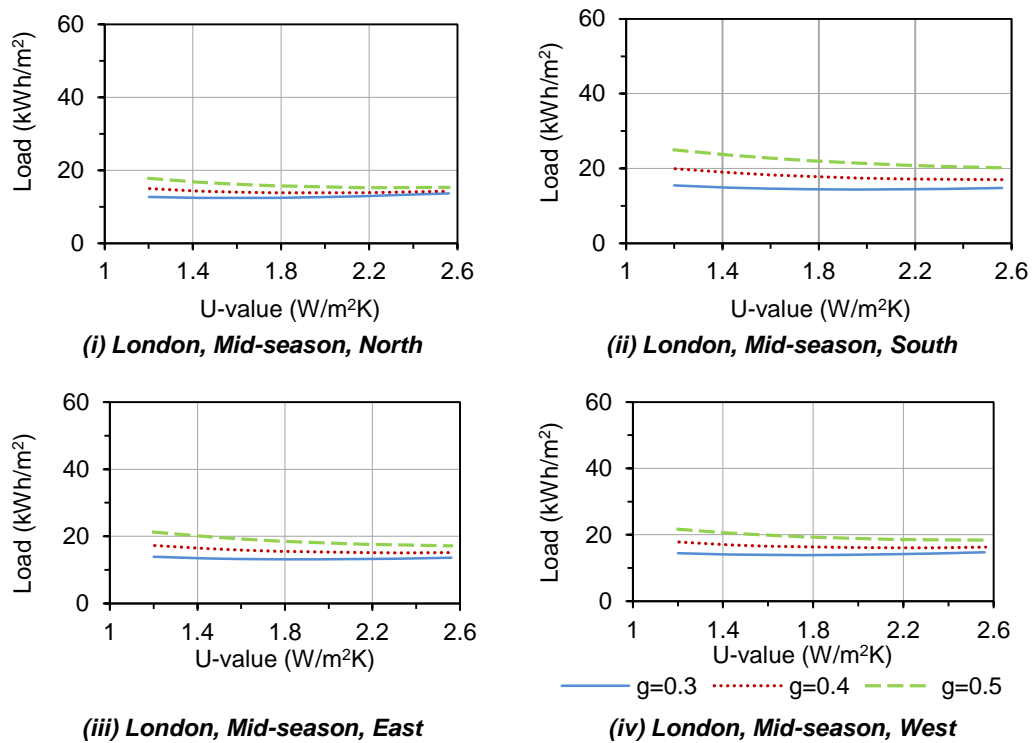


Figure 4.23 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in mid-season, London, SC3

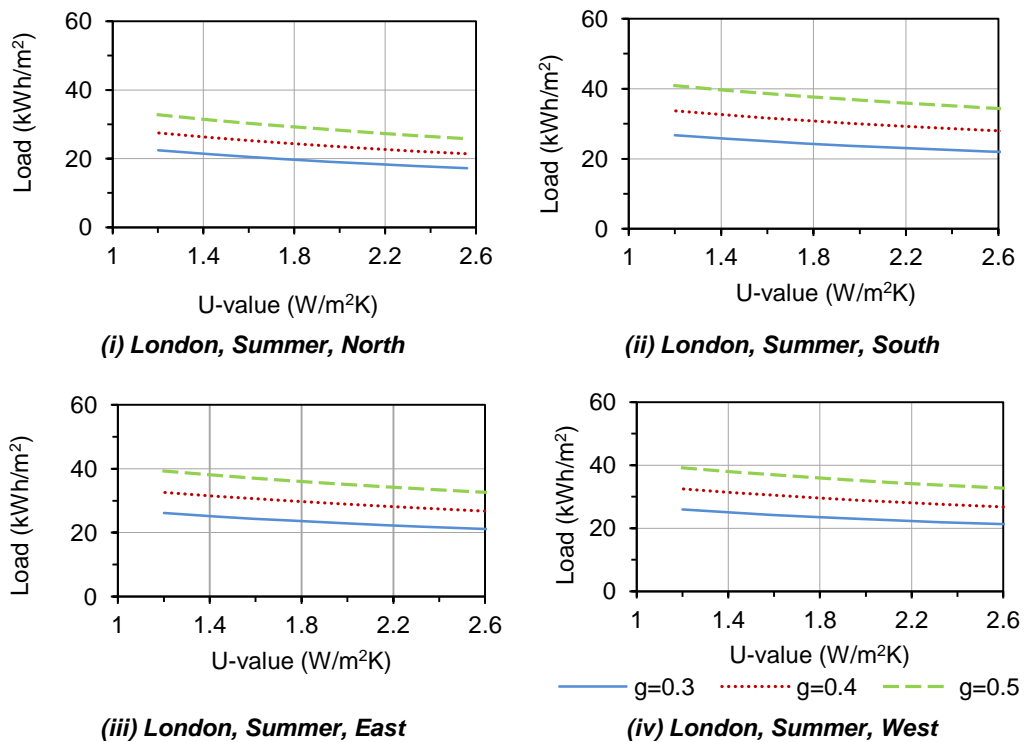


Figure 4.24 Effect of U and g values and building orientation on heating/cooling load of test office TAS in summer, London, SC3

Seasonal heating and cooling breakdown

Figure 4.25 and Figure 4.26 show the nature of energy usage for North, South, East and West facing offices in winter and mid-season. Figure 4.25 shows that in winter, only heating is required and the demand is lowest in South facing office. This is unlike the cases for winter in SC1 where it was found that offices require a mix of heating and cooling due to the higher value of internal heat gain. In all cases, when the U-value decreases, it causes a decrease in the heating demand. Lowering the g-value from 0.5 to 0.3 has little effect on heating demand in winter. In mid-season (Figure 4.26), the majority of energy is required for cooling. There is a small amount of energy required for heating, which increases with increasing U-value. The cooling requirement increases with increasing U-value. The results for summer (not included) show there are only a cooling demand and that lowering the U-value increases cooling load despite the fact that the average outdoor temperatures in London are generally lower than those indoors at this time of the year. Compared with SC1, internal gains are lower and there is more heating load, however the cooling requirement remains a large proportion of the total energy demand.

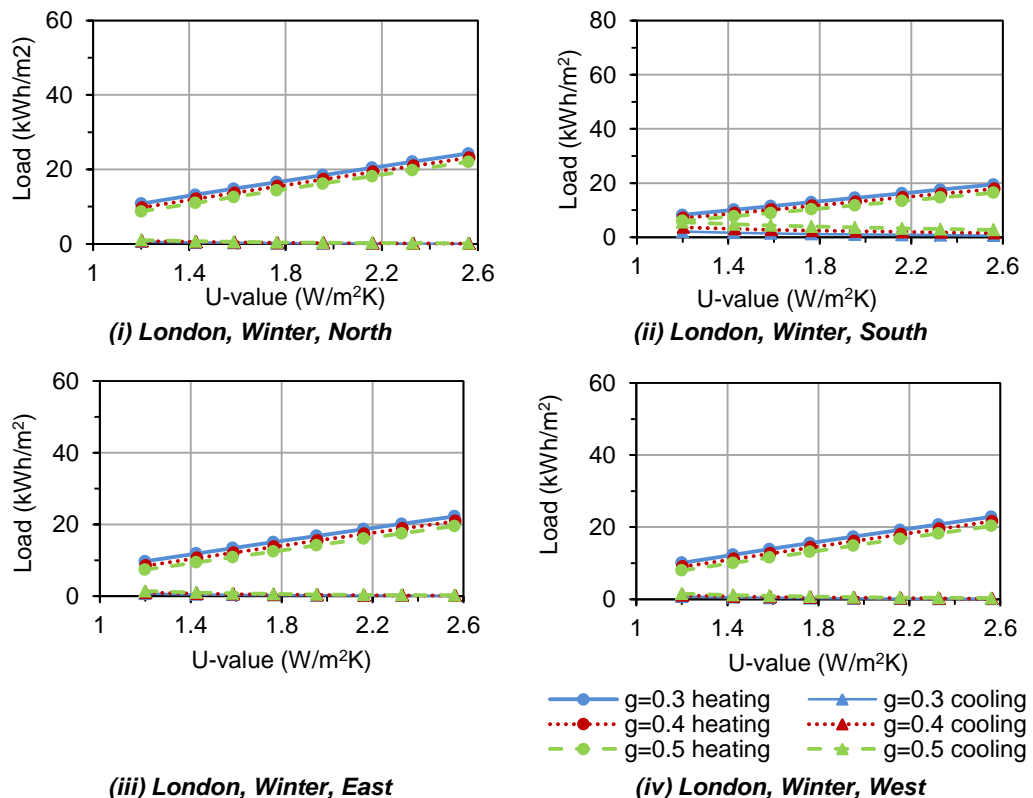


Figure 4.25 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in winter, London, SC3

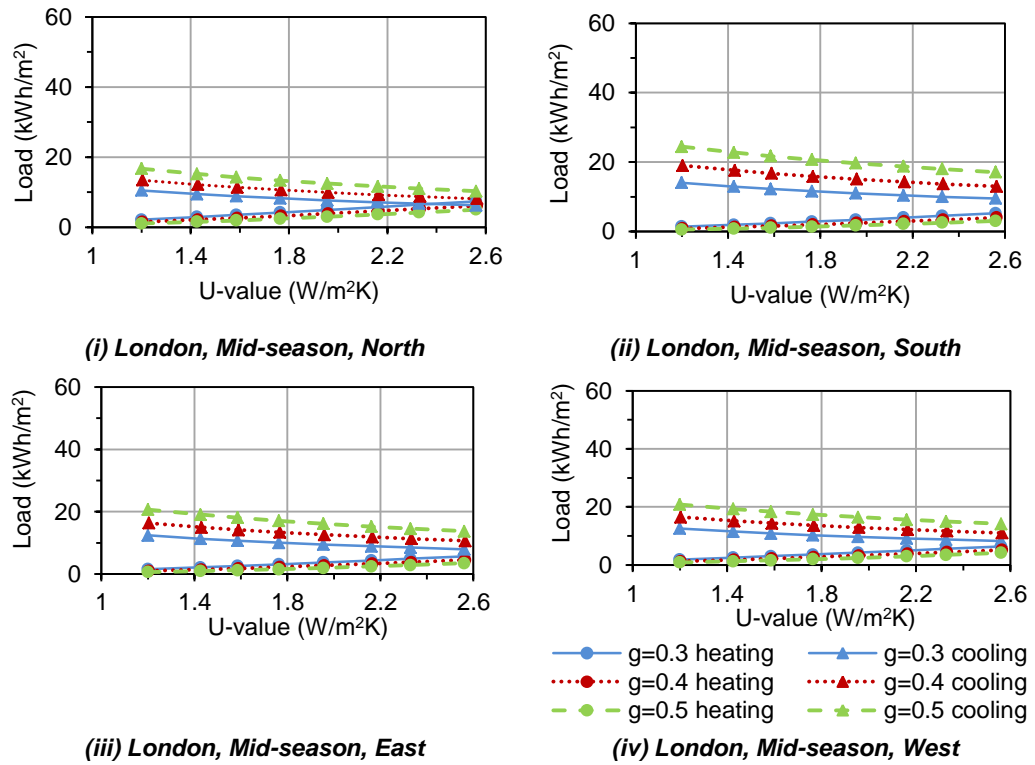


Figure 4.26 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in mid-season, London, SC3

Breakdown of the results

Further insights are obtained by considering values of the principal factors influencing energy demand. Table 4.12 shows the results for South facing offices in winter (W), mid-season (M) and summer (S) assuming $g = 0.5$ and U is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. The values in the table are the summations of hourly energy demand for these seasons.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	6	6	-24	-23	29	22	-4
	2.6	16	3	-40	-23	29	22	-1
M	1.2	1	24	-22	-16	29	37	-5
	2.6	3	17	-34	-16	29	37	-2
S	1.2	0	50	-14	-5	29	44	-4
	2.6	0	46	-20	-5	29	44	-2

Table 4.12 Effect of U-value on energy demand of South facing offices in London assuming $g=0.5$, SC3

Compared with SC1, the value of internal gains are significantly lower at 29kWh/m². The ventilation heat losses are generally lower. The net effect of these changes is cooling loads are lower in summer but heating loads are higher in winter. The reasons behind the seasonal trends remain the same and are briefly described here.

From Table 4.12 it can be seen that in winter if the U-value is 2.6W/m²/K, the heating demand is 16kWh/m². When the U-value is reduced from 2.6 to 1.2 W/m²K, the heating demand also reduces to 6kWh/m² but there is a small increase in the cooling load. Nevertheless, lowering the U-value of a facade reduces the overall energy required and is beneficial. This is unlike the situation in SC1, where heating demand in winter is lower due to higher internal heat gain (Table 4.6), but the cooling demand is more significant and overall facades with lower U-values increase energy demand.

In mid-season the average temperature difference between indoors and outdoors is smaller and this reduces the heat loss due to ventilation from around -23kWh/m² to -16kWh/m². The conduction heat losses are also somewhat lower. Thus in the case of facades with a U-value of 2.6W/m²K the conduction heat loss reduces from 40kWh/m² to 34kWh/m². Moreover, because solar irradiation levels are higher during mid-season compared with winter, Q_{sol} , increases from 22kWh/m² to 37kWh/m². The net effect is still that more energy is required for cooling, even though the average outdoor temperature is still around 11°C lower than the design indoor temperature, and that the internal gain has been reduced by around a third.

In summer the difference between the design indoor and outdoor average temperature is around 5°C, and therefore the Q_{air} further reduces to -5kWh/m², as does the heat loss due to conduction. The sun is stronger during this period and hence Q_{sol} increases to 44kWh/m², and in turn the energy required to regulate building temperatures. Lowering the U-value in summer reduces heat loss due to conduction, thereby, increasing the cooling load, which was also found to be the case in SC1.

Thus, under SC3 condition, lower U-value facades can save a large amount of heating in winter, but increase the cooling load in mid-season and summer. In South facing office, when $g=0.5$, the increase in cooling load is higher than the amount saved in heating. The net effect is that it is an increase in the total energy demand by 2kWh/m².

However, for the rest of cases, lowering the U-value does reduce the annual energy demand. For example, North facing offices when $g=0.5$, shown in Table 4.13. A lower U-value facade can save on heating in winter by an amount which is larger than the increase in cooling load during the mid-season and summer months combined. Annually, it is better to use a facade with a U-value of $1.2\text{W/m}^2\text{K}$.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	9	1	-23	-23	29	6	4
	2.6	22	0	-40	-23	29	6	7
M	1.2	1	17	-21	-16	29	21	3
	2.6	5	10	-35	-16	29	21	6
S	1.2	0	42	-14	-5	29	30	2
	2.6	0	37	-21	-5	29	30	4

Table 4.13 Effect of U-value on energy demand of North facing offices in London assuming $g=0.5$, SC3

The effect of g-value

It appears that the g-value has a more pronounced energy saving effect than U-value. From the annual results (Figure 4.21) it can be seen that facades with lower g-values have lower energy requirements irrespective of orientation. From Figure 4.23 and Figure 4.24, it can be seen that this is particularly true during mid-season and summer. This is probably because offices in London generally require heating during winter, whereas cooling is the dominant load at other times. Table 4.14 shows the effect of g-value on seasonal energy demand in South facing offices assuming $U = 1.2\text{W/m}^2\text{K}$.

	g	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	0.3	8	2	-22	-23	29	12	-1
	0.4	7	4	-23	-23	29	17	-3
	0.5	6	6	-24	-23	29	22	-4
M	0.3	1	14	-18	-16	29	19	-2
	0.4	1	19	-20	-16	29	28	-3
	0.5	1	24	-22	-16	29	37	-5
S	0.3	0	36	-10	-5	29	23	-1
	0.4	0	43	-12	-5	29	33	-3
	0.5	0	50	-14	-5	29	44	-4

Table 4.14 Effect of g-value on energy demand of South facing offices in London assuming $U=1.2 \text{ W/m}^2\text{K}$, SC3

Here it can be seen that lowering the g-value from 0.5 to 0.3 causes a small increase in heating demand. In mid-season and summer, the cooling demand reduces with a reducing g-value largely because of the associated decrease in solar gains. These results show that annual savings of up to around 25 kWh/m^2 are possible with facades with $U=1.2 \text{ W/m}^2\text{K}$ and $g=0.3$.

Summary

Lowering the amount of internal gains reduces the annual energy demand. In winter, due to the reduced amount of Q_{int} , there is an increased amount of heating demand but little cooling demand, which is different from SC1. Consequently, high performance facades can reduce the heating load by over 50%. The effect of lowering the U-value in mid-season cases is quite neutral. In summer, there is a lower cooling load compared with SC2. Even though the internal gains are reduced by a third, the total cooling demand is still higher than the total heating demand. Overall, the facade with $g=0.3$ and $U = 1.2 \text{ W/m}^2\text{K}$ has the best performance.

4.4 Effect of climate change, SC4

This section investigates the effect of climate change on the energy use of offices in London utilising high performance facades. The future weather file, which is the 2050 medium emission is used. It is assumed that offices will be occupied 10 hours a day, 7 days a week, and the internal gains are 33.7 W/m². The results obtained from Tas simulations only are presented and discussed.

London future climate data, 2050

Table 4.15 shows the seasonal average values of hourly temperatures and solar radiation values projected for 2050, medium emission, for London, used in Tas. The climate data shows that London will experience a significant increase in outdoor temperature and some changes in solar irradiance values depending on the seasons. Compared with London's current weather conditions, the seasonal average outdoor temperatures are predicted to increase by 1.1°C, 1.7°C and 3.1°C in winter, mid-season and summer respectively. The solar radiation is projected to be 22kWh/m² lower in winter, but 289kWh/m², 531kWh/m² higher in mid-season and summer respectively. It can be seen that winter is still the coldest time of the year with the least amount of solar radiation, whereas, summer is the hottest time of the year with the highest amount of solar radiation. The indoor design temperature has been set as 22 °C.

London	T _{max} (°C)	T _{min} (°C)	T _{av} (°C)	S (Wh/m ²)
Winter	14.7	1.3	7.9	1467
Mid-season	19.2	3.2	12.2	4069
Summer	27.7	11.1	19.9	5932

Table 4.15 seasonal averaged temperature and solar radiation data for London, 2050

4.4.1 SC4 Annual trends

Figure 4.27 (i, ii, iii, iv) shows the effect of U and g-values on annual energy demand for North, South, East and West facing offices respectively. It can be seen that the trends found in SC4 are very similar to those found in SC1, i.e. utilising facades with low U-values irrespective of office orientations increases the energy demand. Annual energy demand is the highest in South facing offices and the least in North facing offices. It is also found that lowering the g-value from 0.5 to 0.3 can reduce energy demand irrespective of U-value and office orientation. This effect is most obvious in South facing offices. In general, the annual loads found in SC4 are higher than those in SC1 due to the high temperatures and solar irradiation values, as are the seasonal loads which are discussed next.

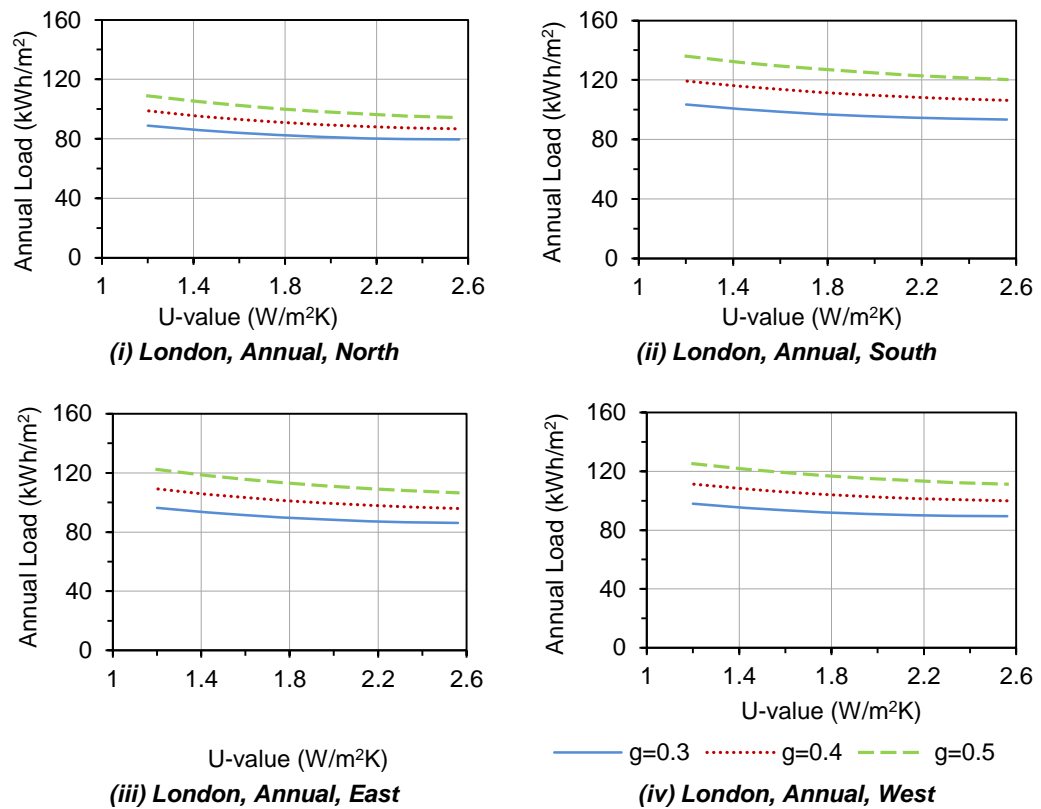


Figure 4.27 Effect of U and g values and building orientation on annual heating/cooling load of test office TAS, London

4.4.2 SC4 Seasonal trends

Figure 4.28, Figure 4.29 and Figure 4.30 show the sum of the heating and cooling loads in winter, mid-season and summer respectively. The trends in SC4 are similar to those found in SC1. From Figure 4.28 it can be seen that in winter, the least amount of energy is required when the facade has a U-value of approximately $2\text{W/m}^2\text{K}$ for North facing offices and between $2.2\text{--}2.6\text{W/m}^2\text{K}$ for offices facing in the three other directions. In South facing offices, lowering the g-value reduces energy demand by a small amount, but has almost no effect on offices facing the three other directions. In the mid-season, (Figure 4.29) the energy demand increases with decreasing U-value. The trend is the same in summer (Figure 4.30); however, the increase in energy demand is smaller when U-value is lowered from 2.6 to $1.2\text{W/m}^2\text{K}$. Because lower U-value facades increase energy demand in two seasons out of three, there is an overall increase in annual energy demand in all cases.

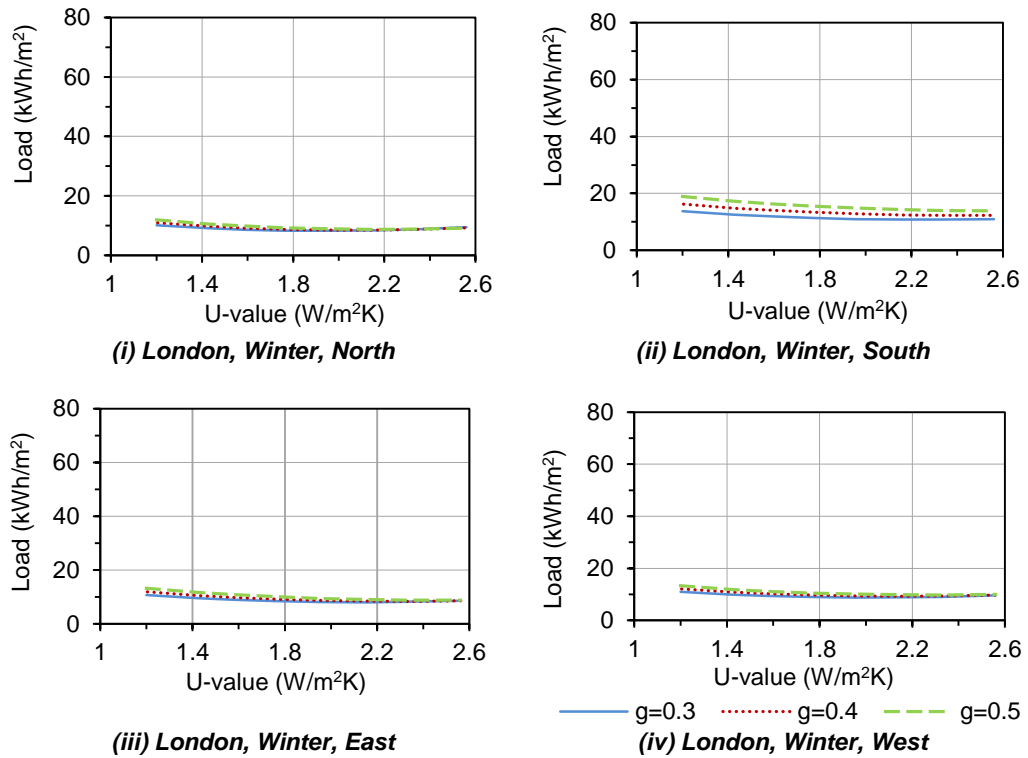


Figure 4.28 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in winter, London, SC4

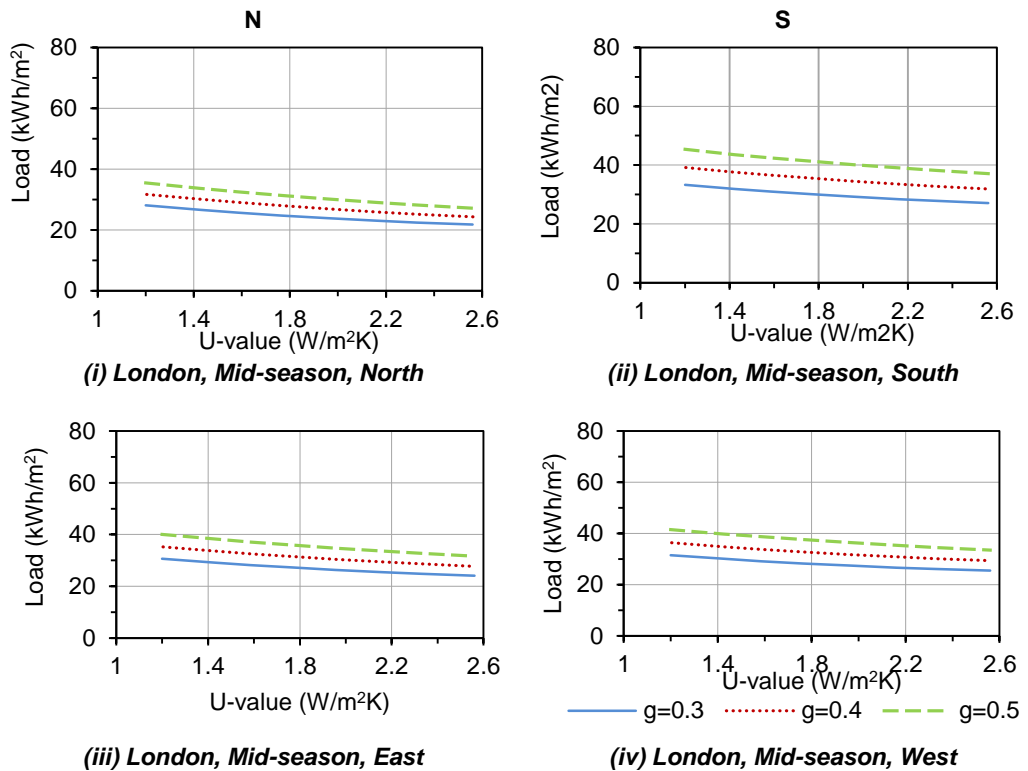


Figure 4.29 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in mid-season, London, SC4

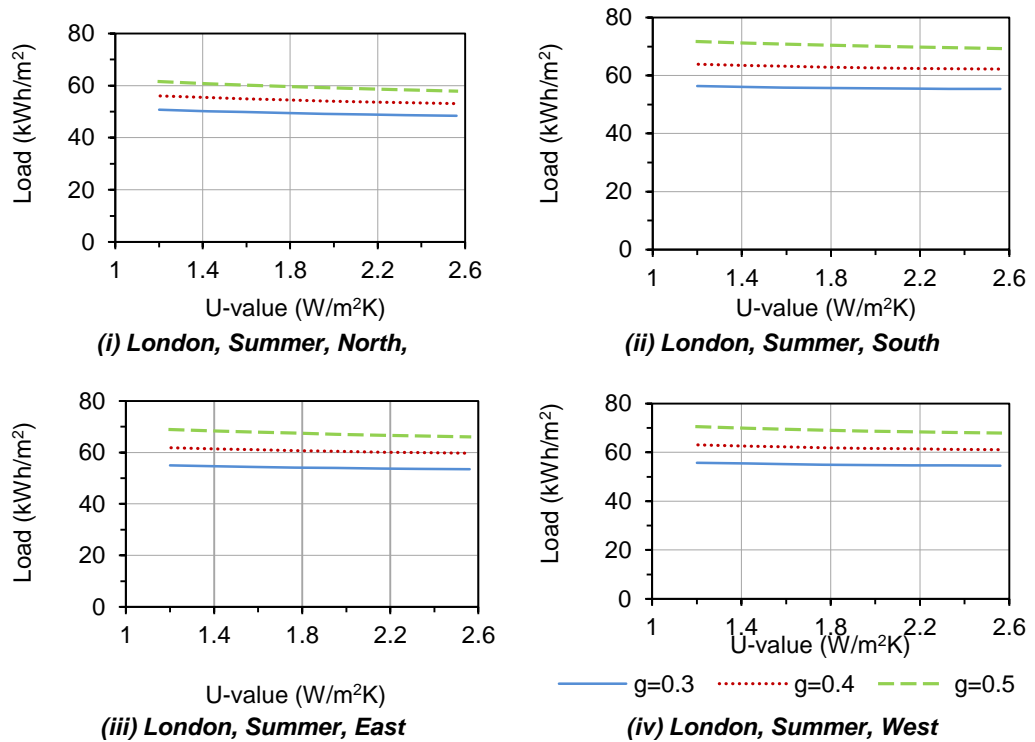


Figure 4.30 Effect of U and g values and building orientation on heating/cooling load of test office TAS in summer, London, SC4

The nature of the energy usage in offices facing North, South, East and West is shown in Figure 4.31 and Figure 4.32 for winter and mid-season respectively. Figure 4.31 shows that in winter, offices require a mix of heating and cooling. These figures also show that South facing offices require more cooling than offices facing other directions. In each case, when the U-value is decreased, the heating demand also decreases but the cooling demand increases. In mid-season, as shown in Figure 4.32, the majority of energy required is for cooling with minimal amounts for heating. Lowering the U-value increases the cooling load. The simulation results for summer (Figure 4.30) show there is only a cooling demand all cases, lowering the U-value does not have much influence on the cooling load. However, lowering the g-value can reduce the cooling requirement in all cases.

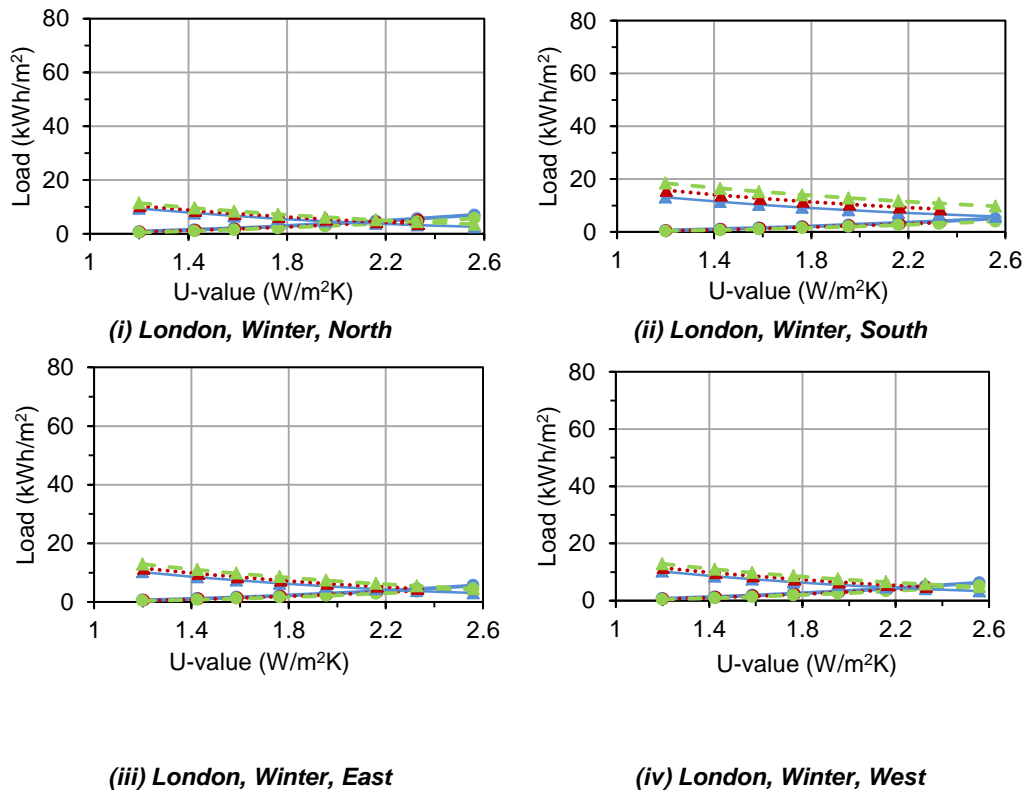


Figure 4.31 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in winter, London, SC4

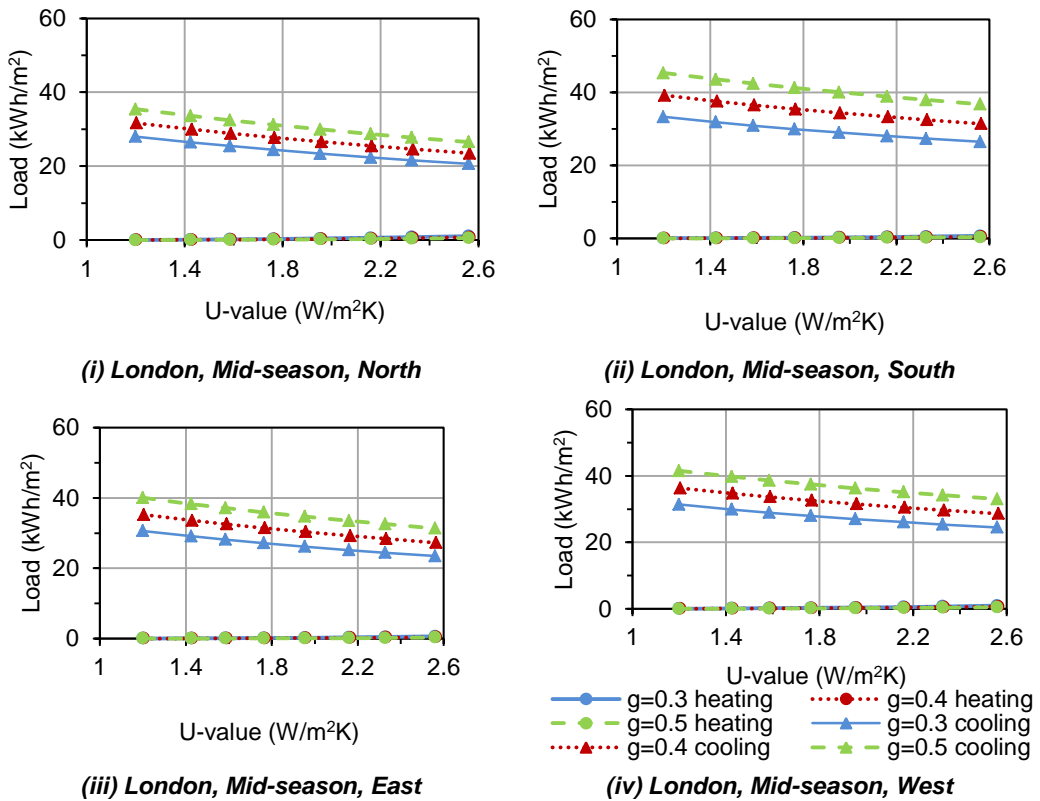


Figure 4.32 Effect of U and g values and building orientation on heating/cooling load of test office using TAS in mid-season, London, SC4

Breakdown of the results

As before a breakdown of principal factors influencing energy demand, namely conduction heat gain/loss through the facade (Q_{cond}) etc. was carried out. Table 4.16 shows the results for South facing offices in winter (W), mid-season (M) and summer (S) assuming $g = 0.5$ and the U-value is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. The values in the table are the summations of the hourly energy demand for these seasons.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	0	19	-23	-19	40	21	-2
	2.6	4	10	-38	-19	40	21	1
M	1.2	0	45	-20	-11	41	39	-4
	2.6	0	37	-31	-11	41	39	-2
S	1.2	0	72	-12	-1	41	47	-3
	2.6	0	69	-16	-1	41	47	-1

Table 4.16 Effect of U-value on energy demand of South facing offices in London assuming $g=0.5$, SC4

From Table 4.16 it can be seen that except in winter, if the U-value is $2.6\text{Wm}^2/\text{K}$ ($Q_h = 4\text{kWh/m}^2$) there is generally only a cooling demand, even though the average outdoor temperatures are lower than those indoors throughout the year (Table 4.15). The results for winter also show that there is an increase in energy demand from 14kWh/m^2 to 19kWh/m^2 when the U-value reduces from 2.6 to $1.2\text{W/m}^2\text{K}$. This is because there is a reduction in heat loss due to conduction via the facade, which not only increases the overall energy load, but also increases the energy required for cooling; this finding is similar to that obtained for winter in SC1.

In the mid-season, the average temperature difference between the design indoor temperature and average outdoor temperature is smaller, which reduces heat loss due to ventilation, Q_{air} , from -19kWh/m^2 to -11kWh/m^2 . The conduction heat losses are also lower. Thus, in the case of facades with a U-value of $2.6\text{W/m}^2\text{K}$, the conduction heat loss reduces from -38kWh/m^2 to -31kWh/m^2 . Moreover, because solar irradiation levels are higher during mid-season when compared with winter (Table 4.15), the heat gain from solar irradiation, Q_{sol} , increases from 21kWh/m^2 to 39kWh/m^2 . The net effect is that more energy is required for cooling despite the fact that the average outdoor temperature is still around 10°C lower than indoors.

In the summer the difference between the indoor and outdoor average temperature is around 2°C. Therefore, the heat loss due to ventilation, Q_{air} , further reduces to -1kWh/m² and the heat loss due to conduction (Q_{cond}) also reduces. As the sun is even stronger during this period, it increases irradiation levels and hence, solar heat gains in the building increase to 45kWh/m², which in turn increases the overall energy required to regulate building temperatures.

The general trends remain the same in SC4 when compared to SC1. From winter, mid-season to summer, the heat losses due to conduction (Q_{cond}) and ventilation (Q_{air}) decrease and the solar heat gain increases. The internal heat gain remains virtually unchanged at 40kWh/m², and is higher than the other factors such as Q_{cond} and Q_{sol} and leads to an overwhelming cooling demand throughout the year. Thus, under the projected future weather condition of London 2050, the facade traps heat inside the building and the provision of low U-value facades exacerbates this condition, thereby increasing energy demand. However, because outdoor dry-bulb temperatures are higher, it is found that there is a higher cooling requirement in all offices in all seasons in SC4 than in SC1.

The effect of g-value

Table 4.17 which shows the effect of g-value on annual energy demand for South facing offices assuming $U=1.2 \text{ W/m}^2\text{K}$. Here it can be seen that the cooling demand reduces with reducing g-value largely because of the associated decrease in solar gains. Thus, a facade with a g-value of 0.3 rather than 0.5 in a South facing tested office can save around 33kWh/m² of energy annually.

The reduction in cooling load made possible by lowering the g-value from 0.5 to 0.3 is similar to that achieved in SC1. This is because in 2050 the solar radiation in winter is projected to be lower, but in mid-season and summer are projected to be higher. However, the overall difference is not significant.

	g	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	0.3	1	13	-21	-19	40	11	0
	0.4	0	16	-22	-19	40	16	-1
	0.5	0	19	-23	-19	40	21	-2
M	0.3	0	33	-16	-11	41	21	-1
	0.4	0	39	-18	-11	41	30	-2
	0.5	0	45	-20	-11	41	39	-4
S	0.3	0	56	-8	-1	41	24	0
	0.4	0	64	-10	-1	41	35	-2
	0.5	0	72	-12	-1	41	47	-3

Table 4.17 Effect of g-value on energy demand of South facing offices in London assuming U=1.2 W/m²K, SC4

Summary

The annual and seasonal trends found in SC4, are similar to those in SC1. Utilising lower U-value facades still does not result in any energy savings. However, lowering the g-value of facades can reduce total annual energy loads.. There is a greater need for cooling load due to rise in outdoor dry-bulb temperatures.

4.5 Summary and conclusions

The effect of a facade's U-value and g-value has been assessed in North, South, East and West facing offices under four conditions. SC1 assumes a normal working week , i.e. 10 hours working, 7 days a week, SC2 assumes prolonged working hours, i.e. 16 hours working, 7 days a week, SC3 assumes internal gains are 25W/m² rather than 33.7W/m² and SC4 considers the effect of climate change.

4.5.1 Results summary

The values used to produce the annual energy demand graphs for these four scenarios are presented in Table 4.18. The effect of lowering the U-value from 2.6W/m²K to 1.2W/m²K was also calculated and values of annual energy demand are also included in the table.

		SC1				SC2				SC3				SC4			
	U	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
g=0.3	1.20	76	83	88	83	122	131	136	131	55	59	62	60	89	96	103	98
	1.43	73	80	85	80	117	126	131	126	57	60	62	61	86	93	100	95
	1.59	72	78	83	78	114	123	127	122	58	61	62	62	84	92	99	94
	1.77	70	76	82	77	110	120	124	119	59	62	63	63	83	90	97	92
	1.96	70	75	80	76	108	117	121	117	61	64	64	65	81	88	96	91
	2.16	69	75	79	76	105	114	119	114	62	65	66	67	80	87	95	90
	2.33	69	74	79	76	104	113	117	113	64	66	67	68	80	87	94	90
	2.56	70	75	79	76	103	111	115	112	66	68	68	70	80	86	93	90
	2.6-1.2	-6	-8	-10	-7	-19	-20	-21	-19	11	9	7	10	-9	-10	-10	-9
g=0.4	1.20	86	95	103	95	133	145	152	144	62	68	73	69	99	109	119	111
	1.43	82	91	99	91	127	139	146	139	63	69	73	70	95	105	116	108
	1.59	80	89	97	89	123	136	143	135	63	69	73	70	93	103	114	106
	1.77	78	87	95	88	120	132	139	132	64	70	73	71	91	101	112	104
	1.96	77	85	93	86	117	129	136	129	65	71	74	72	90	100	110	103
	2.16	76	84	91	85	114	126	133	126	67	72	74	73	88	98	108	102
	2.33	76	83	91	85	112	124	131	124	68	73	75	74	87	97	107	101
	2.56	76	83	90	85	111	122	128	122	70	74	76	76	87	96	106	100
	2.6-1.2	-10	-12	-13	-10	-22	-23	-24	-22	8	6	3	7	-12	-13	-13	-11
g=0.5	1.20	95	107	119	107	144	159	169	158	69	78	87	80	109	122	136	125
	1.43	91	103	114	103	137	153	163	152	69	78	85	79	105	118	132	122
	1.59	89	101	112	101	133	149	159	149	70	78	85	79	103	116	130	119
	1.77	87	98	109	99	130	145	155	145	70	78	85	80	100	114	127	117
	1.96	85	96	107	97	126	142	151	141	71	78	85	80	98	111	125	115
	2.16	84	94	105	95	123	138	148	138	72	79	85	81	97	109	123	114
	2.33	83	93	103	95	121	136	145	136	73	80	85	82	95	108	122	112
	2.56	82	92	102	94	119	133	142	134	75	81	86	83	94	107	120	111
	2.6-1.2	-13	-15	-17	-13	-25	-26	-27	-25	5	3	-1	4	-15	-16	-16	-14

Table 4.18 Effect of U-value and g-value on annual load, London, Tas

It can be seen in Table 4.18 that in a normal office working schedule (SC1), utilising lower U-value facades below the Building Regulation limit of $2.2\text{W/m}^2\text{K}$ increases the office's annual energy demand irrespective of orientation and g-value. When the g-value is 0.3, lowering the U-value increases the annual energy demand by around $6\text{--}10\text{kWh/m}^2$, whereas the amount is $10\text{--}13\text{kWh/m}^2$ in cases with a g-value of 0.4 and $13\text{--}17\text{kWh/m}^2$ when the g-value is 0.5. Hence, a lower U-value facade performs worse when its g-value is higher. The effect of lowering U-value is worse in SC2, it increases the office's annual energy demand by $20\text{ to }25\text{kWh/m}^2$. Lowering the facade's U-value from $2.6\text{ to }1.2\text{W/m}^2\text{K}$ still increases the energy demand in all offices. However, the absolute numbers are slightly higher than those in SC1.

However, when the internal heat gains is lowered (SC3), lowering the U-value reduces the annual energy demand except when $g=0.5$ in South facing office. The energy reduction effect in all cases is most obvious when the g-value is 0.3.

Lowering the g-value from 0.5 to 0.3 always reduces the office's annual energy demand even with the variations in the internal and external conditions. For example, in SC1, it reduces the annual load by 14, 19, 25 or 19kWh/m^2 for the offices facing the North, East, South and West orientations respectively.

Comments on methods

It can be seen that although the absolute values from two methods are different, the results are within the same order of magnitude. It is worth to note that the steady-state method is very crude. It is used to check the Tas results from gross errors. As discussed before, results from simulation program such as Tas are not completely accurate and it is better used for comparison purposes. It is more worth to look at the relative difference, i.e. the trends of increase and decreases in each term, made by varying U-value of the facade and seasons which are the same from these tables. The variations are also reasonable because they fit with the rules of thumb. Hence, it is reasonable to believe that results from Tas are correct.

4.5.2 Further tests of SC3

It can be seen that lowering the U-value of the facades is only beneficial given there is low amount of internal heat gains. The offices with the lowest energy demand have the facades with low U-values, low g-value and low internal heat gains. Therefore, the level of internal gain is a key parameter in designing low energy office buildings in London.

To further confirm the energy performance of offices having lower internal heat gains, three further scenarios are tested. They are 1) offices with lower internal gain with prolonged working hours, 2) offices having lower internal gains under climate change condition 3) offices having lower internal gain, longer working hours under the climate change condition. The g-value is assumed to be 0.3 in all of these scenarios. The results are summarised in Table 4.19. It can be seen that the use of high performance facade is robust to these changes in design conditions.

		SC3, 10 working hours				SC3, climate change				SC3, longer working hours and climate change			
	U	N	E	S	W	N	E	S	W	N	E	S	W
g=0.3	1.20	80	84	87	85	63	68	73	71	87	94	98	96
	1.43	82	86	89	88	64	69	73	71	89	95	100	98
	1.59	84	88	91	89	64	69	74	72	90	96	101	99
	1.77	86	90	92	92	65	70	74	73	92	98	102	101
	1.96	89	93	95	94	66	71	75	74	94	100	104	103
	2.16	92	95	97	97	68	72	76	75	96	102	106	105
	2.33	95	98	99	100	69	73	77	76	98	104	108	107
	2.56	99	101	103	103	71	75	78	78	101	106	110	110
	2.6-1.2	19	17	16	18	8	7	5	8	14	13	12	14

Table 4.19 Annual energy demand results for London SC3 further tests, 1) extended working hour, 2) climate change, 3) extended working hour and climate change assuming g=0.3.

Furthermore, if an office was designed assuming there are lower internal gains, the best facade option would be low U and g values. However, if actual internal gains were higher ('performance gap'), the lower U-value facade would increase instead of reduce the actual energy demand in the designed office. Hence, the actual office would not be as energy efficient as it was expected to be. Therefore, it is important to assess a range of internal gains scenarios during the design stage.

4.5.3 Conclusions

1. Average outdoor temperatures in London are below the design indoor temperature throughout the year yet there is an overall cooling demand in office buildings because of high internal gains.
2. Energy usage is highest in summer and lowest in winter because of the solar radiation profile which exists in London.
3. In general, lowering the U-value increases the energy required for offices in London, irrespective of office orientation. This is because a large proportion of the energy required is for cooling and lowering the U-value reduces conduction heat losses.
4. Facades with U-values below the currently recommended limit of $2.2 \text{ W/m}^2\text{K}$ can reduce the energy required for heating and cooling in office buildings provided that the equipment and lighting produces low internal gains. This solution is robust to uncertainties such as longer working hours and climate change.
5. Longer occupancy hours increase energy demand because internal gains persist for longer periods of time.
6. Climate change will result in higher outdoor temperatures and solar irradiation levels which in combination increase energy demand because of reduced conduction heat losses and higher solar gains.
7. Significant reductions in energy usage are possible by specifying low g-value facades as they reduce solar heat gains.

CHAPTER 5 INFLUENCE OF HIGH PERFORMANCE FACADE ON ENERGY USAGE IN HONG KONG UNDER DIFFERENT EXTERNAL AND INTERNAL CONDITIONS

Introduction

This chapter investigates the influence of high-performance facades on energy usage in office buildings in Hong Kong using the methods described in Chapter 3. Four scenarios are assessed: standard working hours scenario (SC1), prolonged working hours scenario (SC2), lower internal gains scenario (SC3), and scenario 4 (SC4), which assumes the climate conditions predicted for 2050; the test programme is outlined in Table 5.1. For SC1 and SC2, preliminary tests using the steady-state method are carried out alongside the Tas simulation, in order to ensure that the results from Tas simulation are reasonable. Hence, results from the steady-state method are presented first, followed by Tas results. For SC3 and SC4, only Tas simulations were performed. In each case, the heating/cooling load is calculated assuming the use of facades' U-values between 1.2W/m²K and 2.6W/m²K, and g-values from 0.3 to 0.5. All tests are carried out on offices facing North, East, South and West orientations.

Fixed conditions							
Test location: Hong Kong							
Ventilation rate:10 litres per person per second (l/p/s)							
WWR = 0.7							
Indoor temperature: 21-25°C							
Test variables and methods							
Code	U-value (W/m ² K)	g-value	Orientation	Working schedule	Internal gains (W/m ²)	Weather (CIBSE)	Modelling tools
SC1	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10 hrs)	33.7	Current	Steady-state, Tas
SC2	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0700-2300 (16 hrs)	33.7	Current	Steady-state, Tas
SC3	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10 hrs)	25.0	Current	Tas
SC4	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10 hrs)	33.7	Future, 2050	Tas

Table 5.1 Test summary for Hong Kong

As in Chapter 4, for each scenario annual load results are discussed first, which show the influence of U and g-values of facades on the annual energy performance of offices in all orientations. In order to understand the annual trends, the effect of U and g-values on the total energy demand in winter, mid-season and summer is also presented. Further insight into the trends observed is provided by presenting the numerical values of the principal factors which influence energy demand. The effect of

the U and g-values used is discussed with regard to climate conditions characterised by the indoor and outdoor temperature difference and solar irradiance levels. These breakdown values not only help to understand the influence of the individual parameters, but also check if the Tas results are reasonable. At the end of the chapter, a summary table of numerical results used to produce the annual charts is provided, in order to quantify the effect of the U and g-values and for ease of comparison.

5.1 Influence of high-performance facades in Hong Kong offices

This section presents the test results for Hong Kong under the standard working hours scenario (SC1). The test results from using the steady-state method are presented and discussed first, followed by the more detailed and accurate results obtained from Tas simulations.

5.1.1 Steady-state study

Climate data

Table 5.2 shows the seasonal average values of outdoor dry-bulb temperature, T_{out} , design indoor temperature, T_{in} , the difference between indoor and outdoor temperatures, ΔT , and the solar irradiance values for North, South East and West orientations, S_o . As previously noted, winter covers the period November-February, summer June-September and the remaining months are classed as mid-season. The monthly values are used to calculate the seasonal average temperature and solar irradiance values shown in the table.

It can be seen that in Hong Kong winter is the coldest time of the year, when the average outdoor temperature is 2.1°C cooler than the indoor design temperature, which is indicated by the negative ΔT value. Summer is the warmest time of the year, when the average outdoor temperature is 3.3 °C warmer than the inside design temperature. Additionally, for North, East and West orientations, the lowest amount of solar irradiance occurs in winter and the highest in summer, whereas the South orientation has the opposite pattern. The value of solar irradiance on a North-facing facade is the lowest of the four orientations. However, the solar irradiance values for East and West orientations are similar in winter and summer, but have around a 10% difference in mid-season.

	$T_{out} (^{\circ}C)$	$T_{in} (^{\circ}C)$	$\Delta T (^{\circ}C)$	$S_0 (W/m^2)$			
				N	E	S	W
Winter	18.9	21	-2.1	35.4	68.2	118.8	67.7
Mid-season	24	23	1	45.8	70.8	77.1	77.1
Summer	28.3	25	3.3	57.8	87.0	65.1	89.1

Table 5.2 Seasonal average temperatures and solar irradiance data for Hong Kong.

Annual results

Figure 5.1 shows the effect of U-values and g-values on annual energy demand in test offices facing North, South East and West under the SC1 condition. It can be seen that lowering the U-value has a marginal effect on the annual energy demand of the test offices facing all orientations. Lowering the U-values of the facades from 2.6 to 1.2W/m²K decreases annual energy demand by a small amount, whereas lowering the g-value of the facades can reduce energy demand of all the test offices substantially. Lowering the g-value is most effective in South-facing offices.

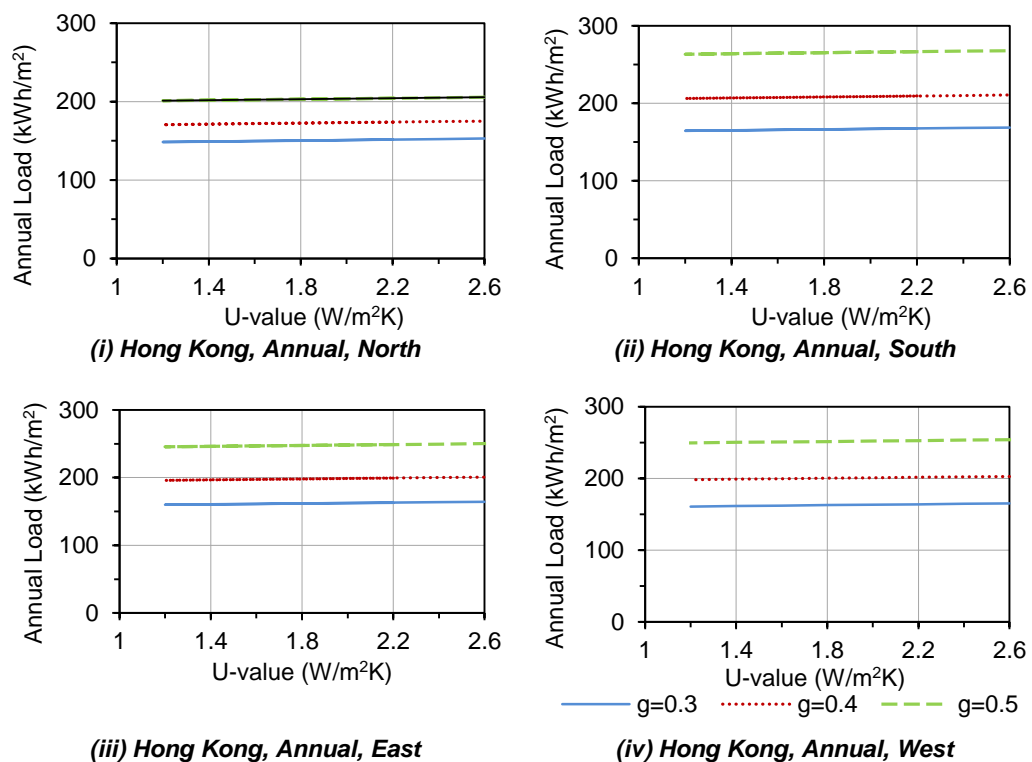


Figure 5.1 Effect of U and g values and building orientation on annual heating/cooling load of test office using steady state calculation, SC1

Seasonal results for Hong Kong, steady-state

In order to understand these patterns, seasonal energy demand patterns were investigated. Figure 5.2 to Figure 5.4 show the energy demand for winter, mid-season and summer using the steady-state method. A positive number indicates an overall net heat gain, representing the amount of cooling load. Conversely, a negative number means an overall net heat loss, giving the heating load, with both loads given in kWh/m².

It can be seen that all the results are positive, net heat gains and therefore only cooling demands in the test offices, irrespective of their orientation. In winter, the outdoor temperatures are somewhat lower than indoors and the results show that the cooling load increases with a decreasing U-value for the facade (Figure 5.2). During mid-season, the provision of a better-insulated facade has very little or no effect on the overall cooling demand. In summer, Figure 5.4 shows that the cooling load declines with a decreasing U-value; this is the opposite of the position in winter, although a cooling load is required in both cases. It is surprising to find that, even though cooling is required for the whole year, the effect of lowering the U-value differs according to the season, whereas lowering the g-value always reduces the cooling demand.

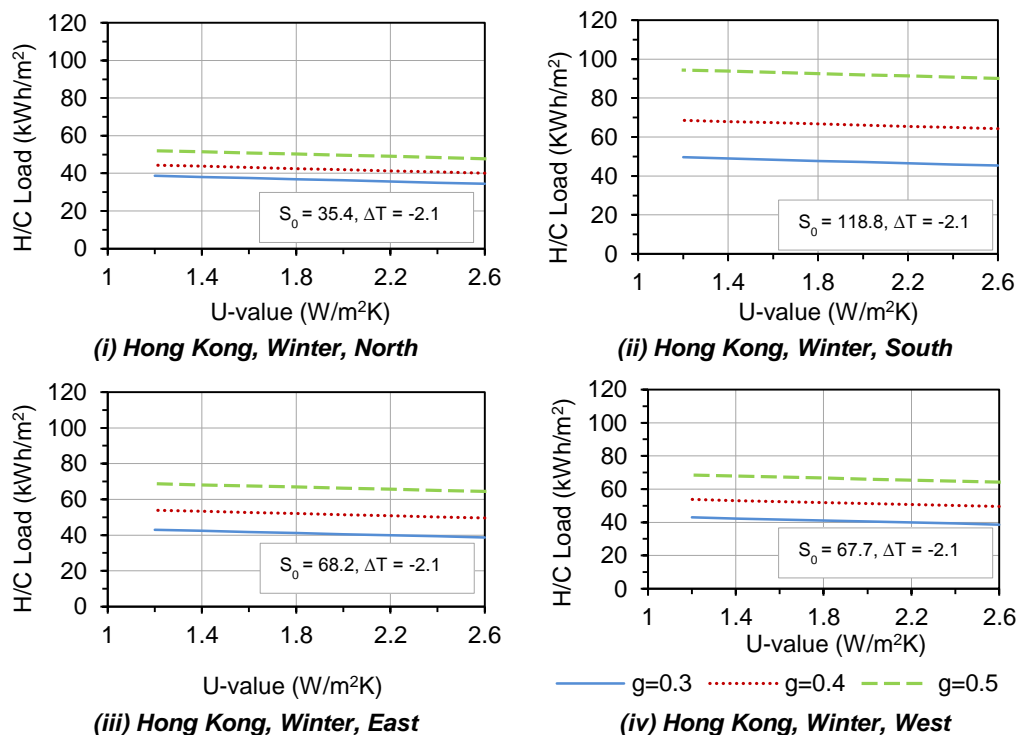


Figure 5.2 Effect of U and g-values and building orientation on heating/cooling load of Hong Kong offices using steady-state calculation in winter, SC1

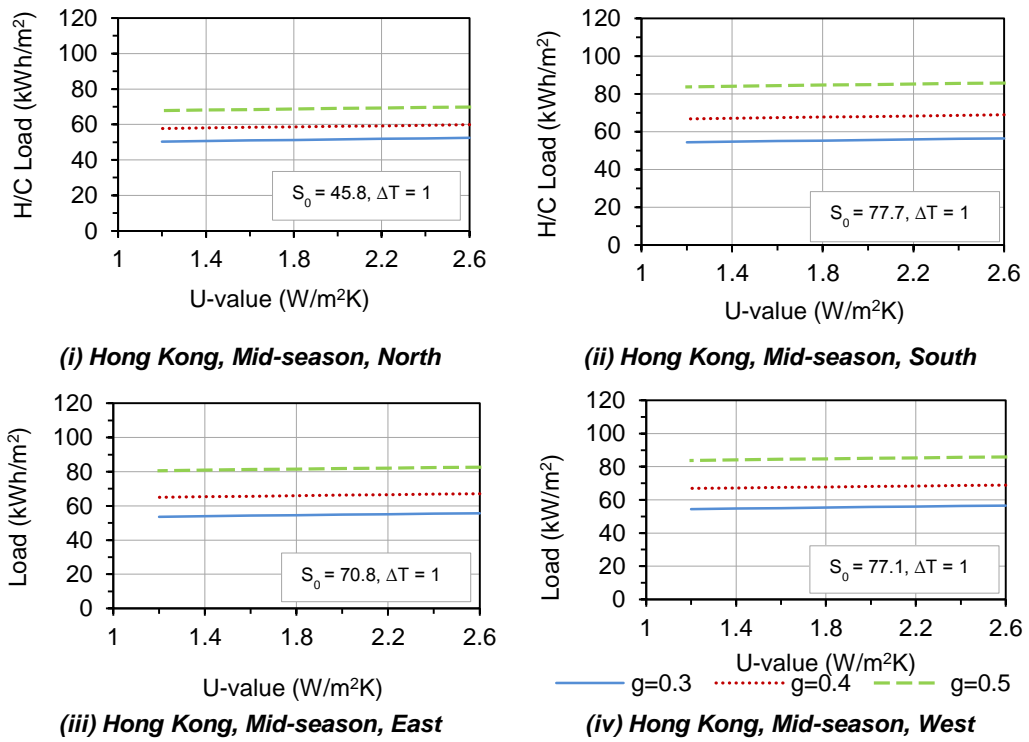


Figure 5.3 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in mid-season, SC1

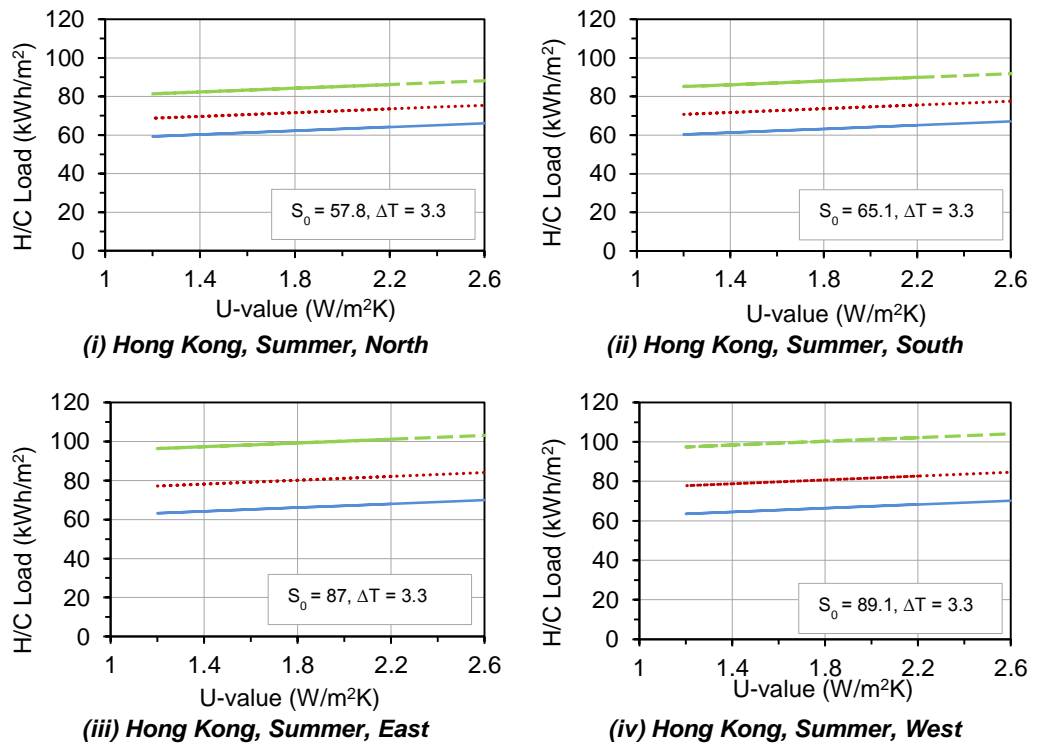


Figure 5.4 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in summer, SC1

Breakdown of the results

The effect of U and g-values can be further explained by looking at the breakdown of the results. Table 5.3 and Table 5.4 show the results for North and South-facing offices assuming $g = 0.5$ and 0.3 , respectively.

The difference in the effect of lowering U-value on the cooling requirements is related to ΔT . As shown in Table 5.2, the average outdoor temperature is around 2°C cooler than the indoor design temperature in winter. From Table 5.3, it can be seen that the provision of better-insulated facades decreases the conduction heat loss when there is large cooling demand. Since the other values are unaffected, the offices with lower U-value facades perform worse than those with higher U-values.

During mid-season the average outdoor temperature is 1°C higher than indoors, and this results in heat gains from conduction as well as ventilation. Lowering the U-value limits the unwanted heat gain from conduction, which causes an increase in the cooling demand. Therefore, using a lower U-value facade is beneficial in mid-season, but the effect is marginal due to the small ΔT .

In summer, $\Delta T = 3.3^{\circ}\text{C}$, therefore there are slightly higher heat gains through conduction and ventilation. The use of a better-insulated facade limits the conductive heat gains, therefore reducing the overall cooling demand.

Generally, lowering the U-value has a very small effect on the seasonal cooling requirement in the test offices irrespective of orientation, because ΔT is small in all seasons and heat gains from internal environment (Q_{in}) and the sun (Q_{sol}) are relatively large. Furthermore, the results are opposite in winter and summer and neutral in mid-season, and lowering the U-value has a marginal effect on the annual loads, irrespective of orientation.

As the heat gain/loss due to conduction and ventilation is small compared to the heat gains from the sun and internal environment (Q_{sol} and Q_{in}), the amount of the cooling required largely depends on the g-value and office orientation. It can be seen in Table 5.3 and Table 5.4 that lowering the g-value from 0.5 to 0.3 reduces the unwanted solar heat gains and in turn the cooling requirement irrespective of season, orientation and U-value. Consequently, it reduces the annual cooling load by 53kWh/m^2 and 100kWh/m^2 in the North and South facing offices respectively, regardless of the U-value. As South facing offices experience higher solar heat gains, they require more cooling than North facing offices and lowering the g-value is more effective. Therefore, it can

be seen that lowering g-value of facades is more crucial than reducing U-value in reducing energy demand in offices in Hong Kong.

Furthermore, it can be seen that the solar heat gain increases from winter to summer in North-facing offices but decreases in South-facing ones. The resulting effect is that the cooling requirement increases from winter to summer in North-facing offices due to the increase in the solar heat gain, as well as the heat gains due to conduction. In South-facing offices when $g = 0.5$, the solar heat gain in winter is high compared with that in mid-season and summer. Therefore, the cooling requirement in winter is higher than in summer, despite there being a favourable heat loss due to conduction in winter. However, this not the case when g is reduced to 0.3 in South-facing offices. This is understandable because the effect of seasonal variations in the solar heat gain is smaller in the overall energy balance, due to the reduced g -value.

	U	North					South				
		Q_c	Q_{cond}	Q_v	Q_{int}	Q_{sol}	Q_c	Q_{cond}	Q_v	Q_{int}	Q_{sol}
W	1.2	52	-4	-3	41	18	95	-4	-3	41	61
	2.6	48	-8	-3	41	18	91	-8	-3	41	61
M	1.2	68	2	1	41	23	84	2	1	41	39
	2.6	70	4	1	41	23	86	4	1	41	39
S	1.2	81	6	5	41	30	85	6	5	41	33
	2.6	88	13	5	41	30	92	13	5	41	33

Table 5.3 Effect of U-value on energy demand of South-facing offices in Hong Kong using steady-state calculation, assuming $g = 0.5$

	U	North					South				
		Q_c	Q_{cond}	Q_v	Q_{int}	Q_{sol}	Q_c	Q_{cond}	Q_v	Q_{int}	Q_{sol}
W	1.2	39	-4	-3	41	5	50	-4	-3	41	16
	2.6	35	-8	-3	41	5	46	-8	-3	41	16
M	1.2	50	2	1	41	6	54	2	1	41	10
	2.6	52	4	1	41	6	57	4	1	41	10
S	1.2	59	6	5	41	8	60	6	5	41	9
	2.6	66	13	5	41	8	67	13	5	41	9

Table 5.4 Effect of U-value on energy demand of South-facing offices in Hong Kong using steady-state calculation, assuming $g = 0.3$

5.1.2 Annual results of Hong Kong, Tas

Climate data

Table 5.5 shows the seasonal average values of the hourly climate data used in the Tas simulations. Winter is the coldest time of the year with the least amount of solar irradiance, whereas summer is the hottest time of the year with the largest solar irradiance. The indoor design temperature has been set as 21 to 25°C. Hence, in winter the outdoor air is colder than the indoor design condition, whereas in summer the average outdoor temperature is around 3.2 °C hotter than the indoor design temperature. The data is similar to the climate data found in the literature used for the steady-state calculations, confirming that the Tas climate file is correct and can be used.

Hong Kong	T_{\max} (°C)	T_{\min} (°C)	T_{av} (°C)	Solar radiation (Wh/m ²)
Winter	24.1	13.5	17.7	3,769
Mid-season	28.4	18.1	23.2	4,008
Summer	31.9	24.4	28.2	4,856

Table 5.5 Seasonal average temperature and solar radiation data for Hong Kong, Tas

Annual results

Figure 5.5 (i, ii, iii, iv) shows the effect of the U-value and g-value on annual energy demand for tested offices in Hong Kong for North, South, East and West orientations obtained from Tas simulations under the SC1 condition. The annual energy demand in the test offices is found to be in the range of 140kWh/m² to 200kWh/m². Additionally, it is higher in South and West-facing offices than in North and East-facing ones. Lowering the U-value has a marginal effect on annual energy demand; it increases the annual energy demand in most of the test offices. Lowering the g-value from 0.5 to 0.3 can reduce the annual energy demand of the test offices, irrespective of the U-value and orientation. The energy-saving effect of lowering the g-value is more obvious in the test offices facing South and West.

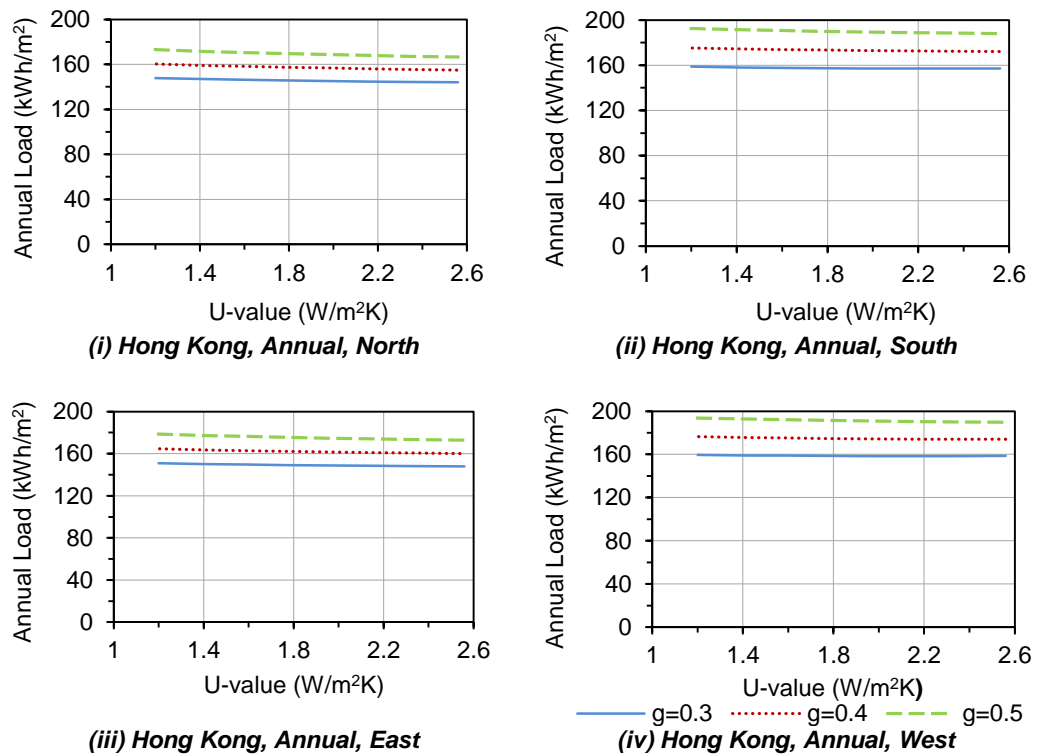


Figure 5.5 Effect of U and g values and building orientation on annual heating/cooling load of test office Tas, Hong Kong, SC1

5.1.3 Seasonal performance of Hong Kong, Tas

In order to understand these results, the energy demand by season is determined. Figure 5.6 to Figure 5.8 show the energy required by the test offices facing all orientations in winter, mid-season and summer, respectively. The simulation results used to generate Figure 5.6 to Figure 5.8 (not presented here) show that there is a cooling load all year round and no heating requirement. The cooling requirements in all test offices are the lowest in winter, between 25kWh/m² and 60kWh/m². In mid-season, the cooling requirements range from 50kWh/m² to 70kWh/m²; it is highest in summer, from 60kWh/m² to 90kWh/m².

The effect of lowering the facade's U-values on the energy demand of the test offices is different under the three seasonal conditions, whereas lowering the g-value of the facade always reduces the cooling requirement. In winter (Figure 5.6), the cooling load increases with decreasing U-values. During mid-season (Figure 5.7), the U-value appears to have no discernible effect on the energy demand. In summer, there is a slight decrease in the cooling requirement with a decreasing U-value (Figure 5.8). Therefore, the overall effect of the U-value on the annual energy demand of the test offices is small, whereas lowering the g-value can reduce the annual energy demand of the test offices.

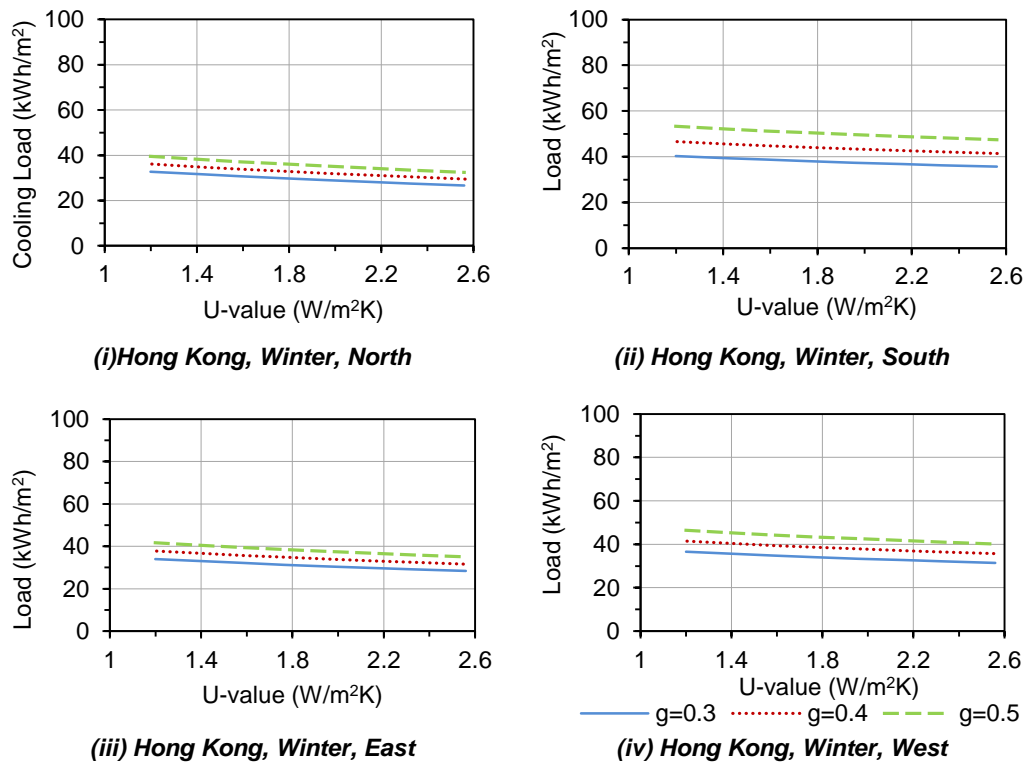


Figure 5.6 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Hong Kong, SC1

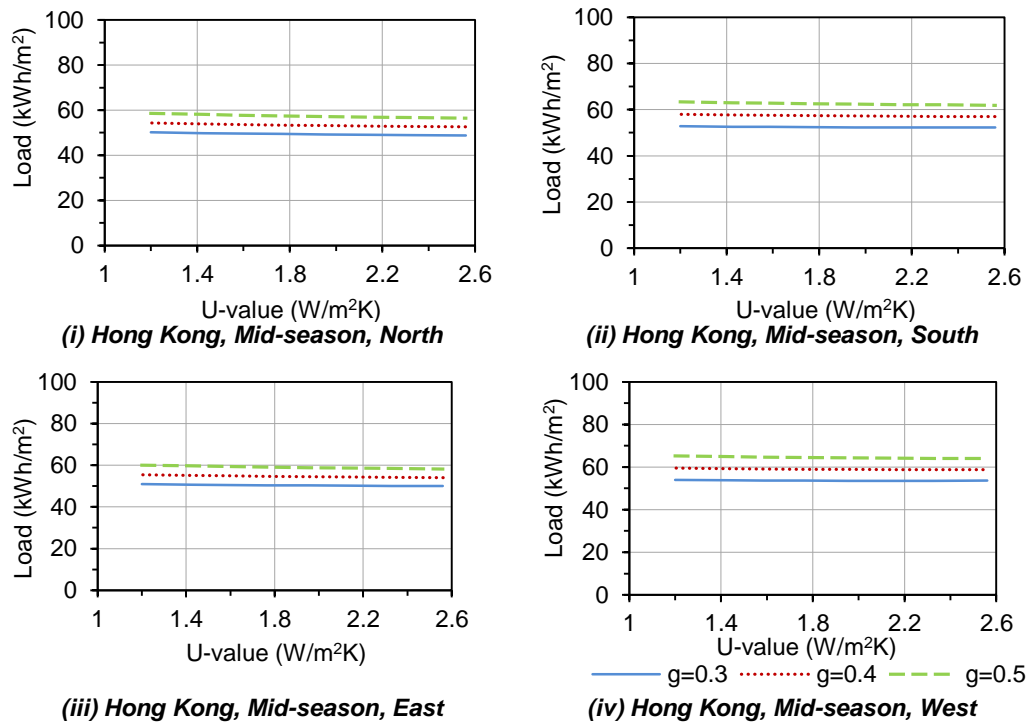


Figure 5.7 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Hong Kong, SC1

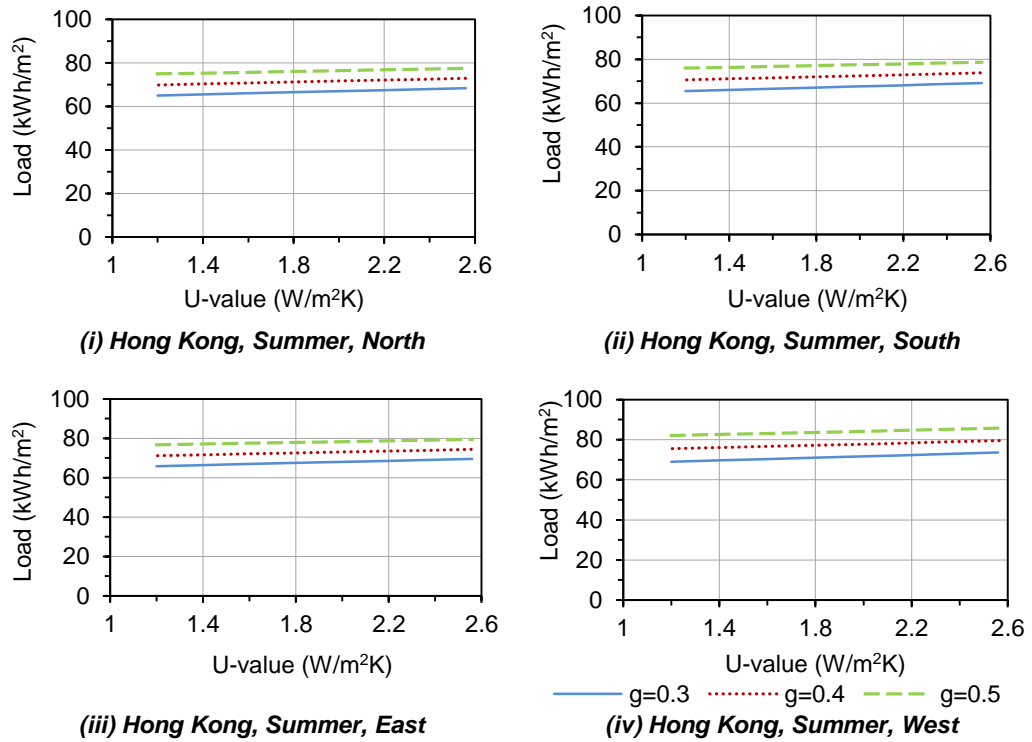


Figure 5.8 Effect of U and g-values and building orientation on heating/cooling load of test office under Tas in summer, Hong Kong, SC1

Breakdown of the results

Further insights are obtained by considering the values of the principal factors influencing energy demand:

- Conduction heat gain/loss through facade (Q_{cond} , kWh/m²)
- Ventilation heat gain/loss (Q_{air} , kWh/m²)
- Internal heat gain (Q_{int} , kWh/m²)
- Solar heat gain (Q_{sol} , kWh/m²)
- Heat gain/loss from adjacent spaces due to building heat transfer (Q_b , kWh/m²)

Note that Q_h and Q_c represent the heating and cooling load (both in kWh/m²), respectively. Q_b measures the heat gain/loss through internal building elements, e.g. walls, floors, ceilings and heat temporarily stored in the air (EDSL 2015). This is not discussed within these results, as the difference it makes is small compared with the other components of the heat balance. Additionally, it does not affect the overall results; this applies to all following cases in this chapter.

Table 5.6 shows the energy load breakdown for winter, mid-season and summer, assuming $g = 0.5$ and $U = 1.2\text{Wm}^2/\text{K}$ or $2.6\text{Wm}^2/\text{K}$. It can be seen that there is no heating demand and cooling necessary all year round. In winter, the provision of better-

insulated facades decreases the Q_{cond} from -24kWh/m^2 to -17kWh/m^2 ; this causes an increase in the energy required for cooling by 5kWh/m^2 .

During mid-season, the indoor and outdoor temperatures are virtually identical (Table 5.5). Therefore, both the conduction and ventilation heat losses are lower, and these cause an increase in the cooling requirement. This would be higher still, were it not for the fact that during mid-season a South-facing office experiences a reduction in solar irradiation, which reduces the solar heat gain from 43kWh/m^2 to 33kWh/m^2 . As the temperature difference between outdoors and indoors is small, lowering the U-value of the facade makes little impact.

In summer, the outdoor temperature is on average around 3°C higher than indoors, and from Table 5.6 it can be seen that in the case of facades with a U-value of $2.6\text{Wm}^2/\text{K}$ this results in heat gains from conduction and ventilation. However, the sun is at its weakest during this period, and therefore Q_{sol} is lowest, but the energy demand is higher than at mid-season. Using a facade with a lower U-value reduces conductive heat gains, which in turn reduces the overall energy demand.

Overall it can be seen that, due to the small temperature difference between outdoors and indoors, the provision of a low U-value facade only has a small effect on the conduction heat gain/loss, which influences energy demand in all seasons, especially in mid-season and summer. As the results are opposite in winter and summer, and neutral in mid-season, the provision of a low U-value facade has a slight negative effect on the annual energy demand.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	0	53	-17	-9	40	43	-5
	2.6	0	47	-24	-9	40	43	-3
M	1.2	0	63	-9	-1	41	33	-1
	2.6	0	62	-11	-1	41	33	0
S	1.2	0	76	-2	6	41	31	0
	2.6	0	79	1	6	41	31	0

Table 5.6 Effect of U-value on energy demand of South-facing offices in Hong Kong assuming $g = 0.5$ using Tas, SC1

Effect of g-value

From the annual results (Figure 5.5), it can be seen that facades with lower g-values have lower energy requirements in Hong Kong. From Figure 5.6 to Figure 5.8, it can further be seen that this is true for all office orientations and seasons. Table 5.7 shows the effect of the g-value on seasonal energy demand for South facing offices in Hong Kong. Table 5.7 shows that the energy demand falls with a reducing g-value, largely because of the decrease in solar gains. Lowering the facade's g-value from 0.5 to 0.3, when $U = 1.2\text{W/m}^2\text{K}$ in a South-facing tested office, can reduce the cooling demand in winter, mid-season and summer, by 13kWh/m^2 , 10kWh/m^2 and 10kWh/m^2 respectively, and hence it lowers the annual energy demand by 33kWh/m^2 .

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	0	40	-13	-9	40	22	-1
	0.4	0	47	-15	-9	40	33	-3
	0.5	0	53	-17	-9	40	43	-5
M	0.3	0	53	-5	-1	41	17	1
	0.4	0	58	-7	-1	41	25	0
	0.5	0	63	-9	-1	41	33	-1
S	0.3	0	66	1	6	41	16	1
	0.4	0	71	0	6	41	23	1
	0.5	0	76	-2	6	41	31	0

Table 5.7 Effect of g-value on energy demand of South-facing offices in Hong Kong, assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC1

5.2 Effect of prolonged working hours, SC2

This section presents the results for Hong Kong under a prolonged working hours scenario which considers 16 working hours per day, 7 days a week, with assumed internal gains of 33.7kWh/m^2 under Hong Kong's current climate conditions. Results obtained from using the steady-state method are presented first followed by results from Tas.

5.2.1 Steady-state study

Annual results

Figure 5.9 shows the annual energy demand in the test offices facing North, South, East and West in Hong Kong. As in SC1, lowering the U-value has a marginal effect on the annual energy demand, whereas lowering the g-value is more effective, particularly in South-facing offices. In general, the annual loads in test offices are higher in SC2 than in SC1.

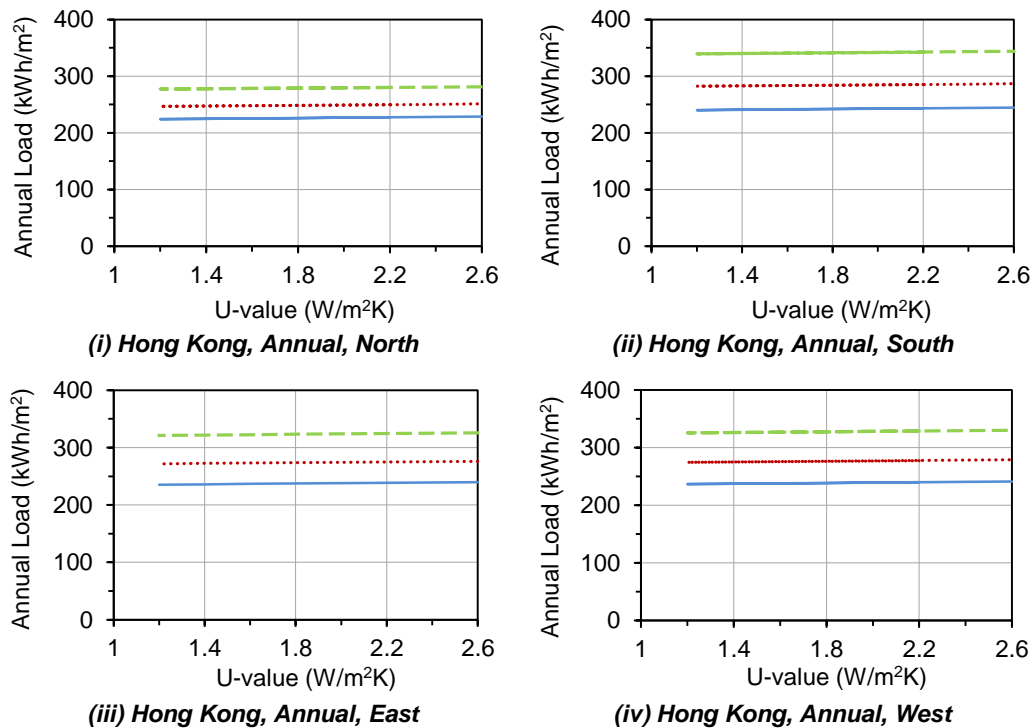


Figure 5.9 Effect of U and g-values and building orientation on annual heating/cooling load of test office using steady state-calculation, Hong Kong, SC2

Seasonal results for Hong Kong

Seasonal energy demand results for winter, mid-season and summer are shown in Figure 5.10, Figure 5.11 and Figure 5.12 respectively. Lowering the U-value of the facade increases the cooling demand in all the test offices in winter; it has very little

effect in mid-season, but decreases the cooling demand in summer. These seasonal results are similar to those found in SC1.

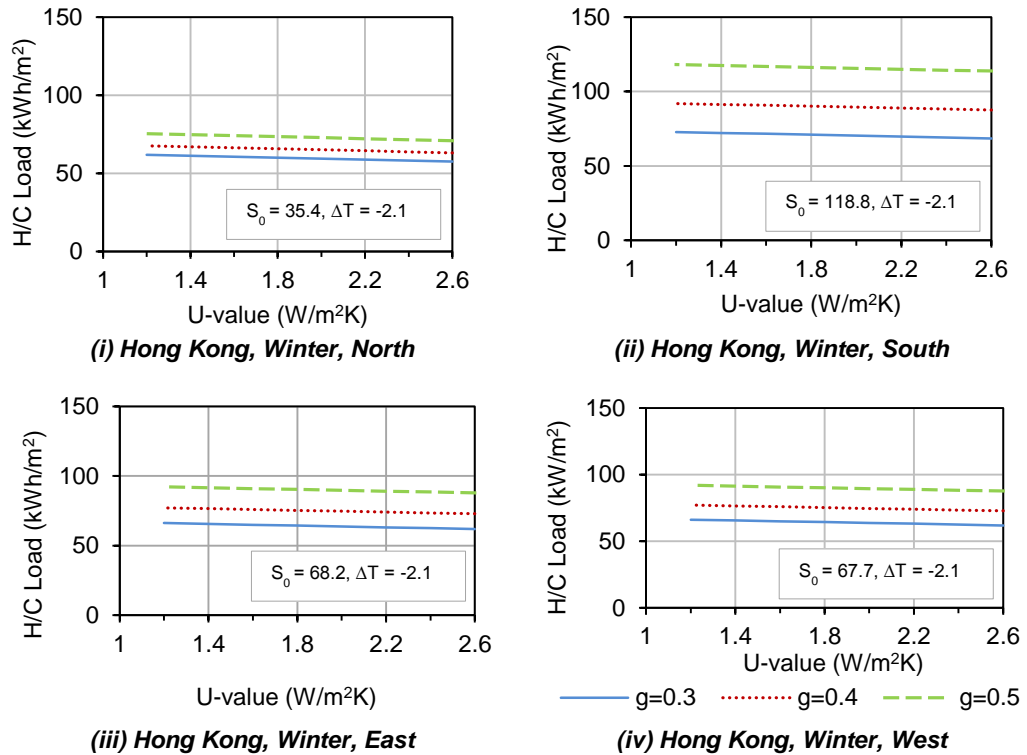


Figure 5.10 Effect of U and g values and building orientation on heating/cooling load of test office using steady-state calculation in winter, Hong Kong, SC2

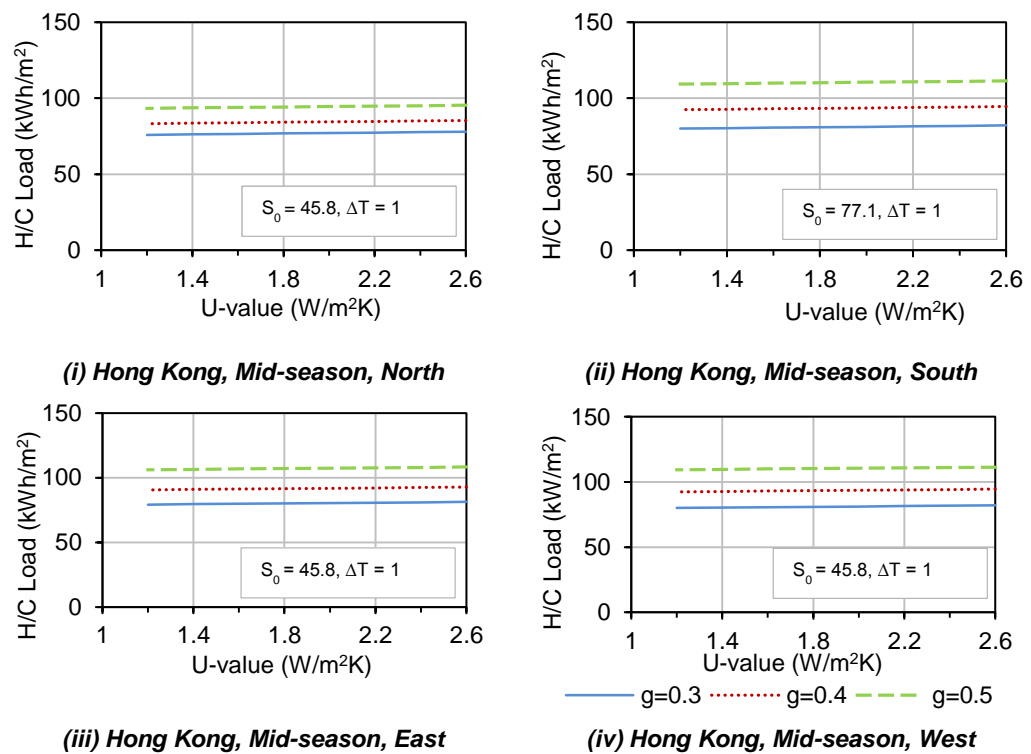


Figure 5.11 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in mid-season, Hong Kong, SC2

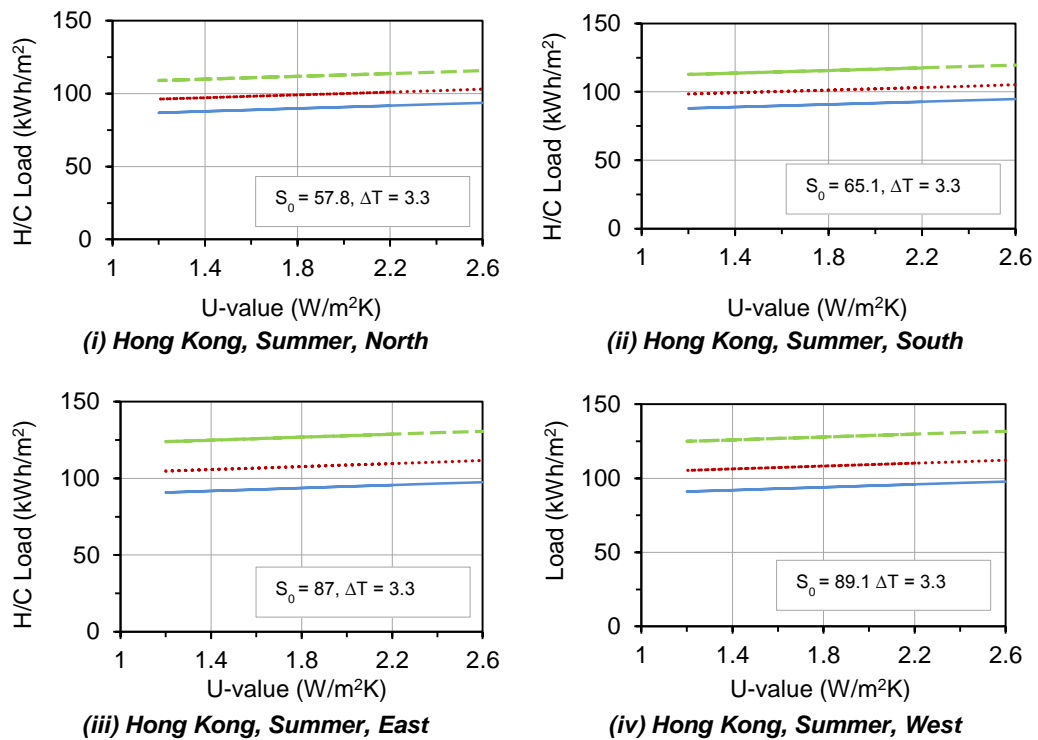


Figure 5.12 Effect of U and g values and building orientation on heating/cooling load of test office using steady-state calculation in summer, Hong Kong, SC2

Breakdown of the results

Table 5.8 and Table 5.9 show the effect of lowering the U-value from $2.6 \text{ W/m}^2\text{K}$ to $1.2 \text{ W/m}^2\text{K}$ on values of the principal terms in the heat balance equation for each season in North and South-facing offices, respectively, assuming $g = 0.5$ and $g = 0.3$. The internal heat gain rises from 41 kWh/m^2 to 66 kWh/m^2 due to the longer working hours. However, the heat loss due to conduction stays the same and there is an increase in the heat loss due to ventilation. Overall, there is a higher cooling requirement over all seasons. Lowering the facade's g-value from 0.5 to 0.3 can reduce the cooling load in all seasons, and hence the annual loads in the test offices.

		North					South				
	U	Q	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}
W	1.2	75	-4	-5	66	18	118	-4	-5	66	61
	2.6	71	-8	-5	66	18	114	-8	-5	66	61
M	1.2	93	2	2	66	23	109	2	2	66	39
	2.6	95	4	2	66	23	111	4	2	66	39
S	1.2	109	6	8	66	30	113	6	8	66	33
	2.6	116	13	8	66	30	119	13	8	66	33

Table 5.8 Effect of U-value on energy demand of North and South facing offices in Hong Kong assuming $g = 0.5$ using steady-state calculation, SC2

		North					South				
	U	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}
W	1.2	62	-4	-5	66	5	73	-4	-5	66	16
	2.6	58	-8	-5	66	5	69	-8	-5	66	16
M	1.2	76	2	2	66	6	80	2	2	66	10
	2.6	78	4	2	66	6	82	4	2	66	10
S	1.2	87	6	8	66	8	88	6	8	66	9
	2.6	94	13	8	66	8	95	13	8	66	9

Table 5.9 Effect of U-value on energy demand of North and South-facing offices in Hong Kong assuming $g = 0.3$ using steady-state calculation, SC2

5.2.2 Annual results for Hong Kong, Tas

Figure 5.13 (i, ii, iii, iv) shows the effect of U-values and g-values on annual energy demand in test offices facing North, South, East and West obtained from Tas simulations under the SC2 condition in Hong Kong. In general, extending the working hours from 10 to 16 increases the annual load from around 140 to 200kWh/m² (SC1, Figure 5.5) to 210 to 270kWh/m² (SC2). Lowering the U-value either has no effect or can increase the annual load in the offices by a small amount, which is also observed for SC1. However, lowering the g-value of the facades still reduces the annual energy demand in the test offices by 25 to 35kWh/m².

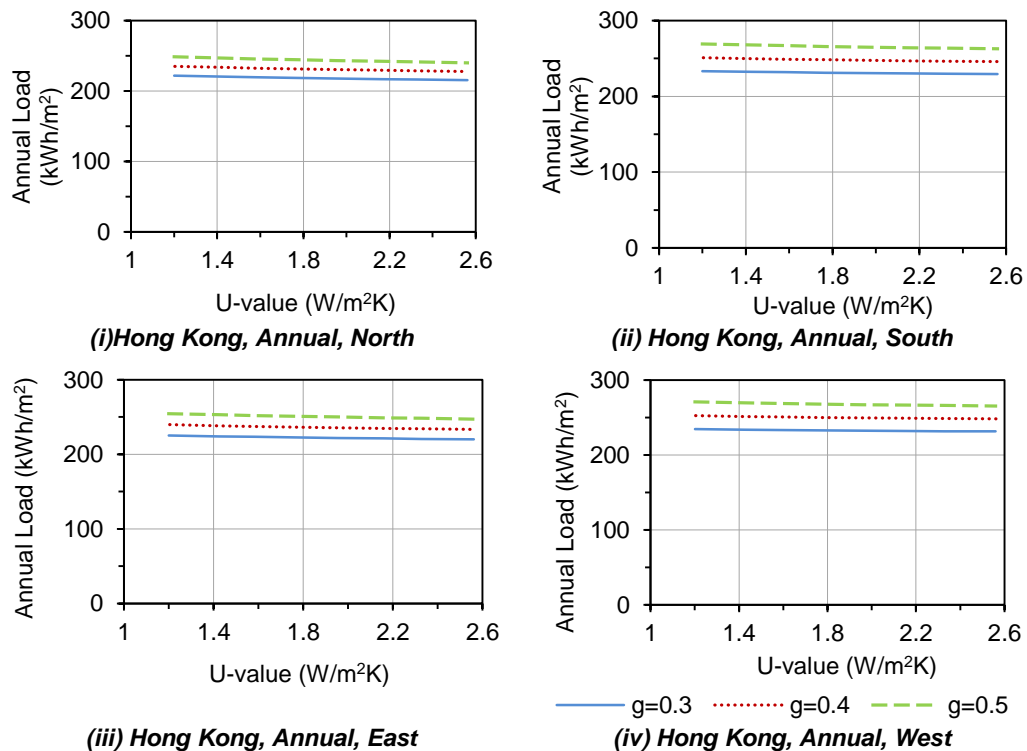


Figure 5.13 Effect of U and g-values and building orientation on annual heating/cooling load of test office, Tas, Hong Kong, SC2

5.2.3 Seasonal results of Hong Kong from Tas

In order to understand the annual results, the energy demand by season was determined. Figure 5.14, Figure 5.15 and Figure 5.16 show the energy required in winter, mid-season and summer respectively, for offices facing North, South, East and West in Hong Kong under SC2. Tas simulation results in Figure 5.14 to Figure 5.16 show that cooling is needed all year round and there is no heating requirement. In general, cooling requirements are lowest in winter, with a range of 40kWh/m² to 80kWh/m². In mid-season, the range is from 70kWh/m² to 100kWh/m², and in summer 90kWh/m² to 120kWh/m². These values are higher than those found for SC1 conditions, in which the total load in the test offices has a range of 25kWh/m² to 60kWh/m² in winter, 50kWh/m² to 70kWh/m² in mid-season and 60kWh/m² to 90kWh/m² in the summer months.

Seasonal energy demand results under SC2 conditions show similar patterns to those in SC1. The general seasonal trends are that in winter, lowering facade's U-value in the tested offices leads to a slight increase in energy demand; in mid-season, the impact of changing U-value is very little; and in summer, the use of a facade with a low U-value in the test offices can reduce energy demand by a small amount.

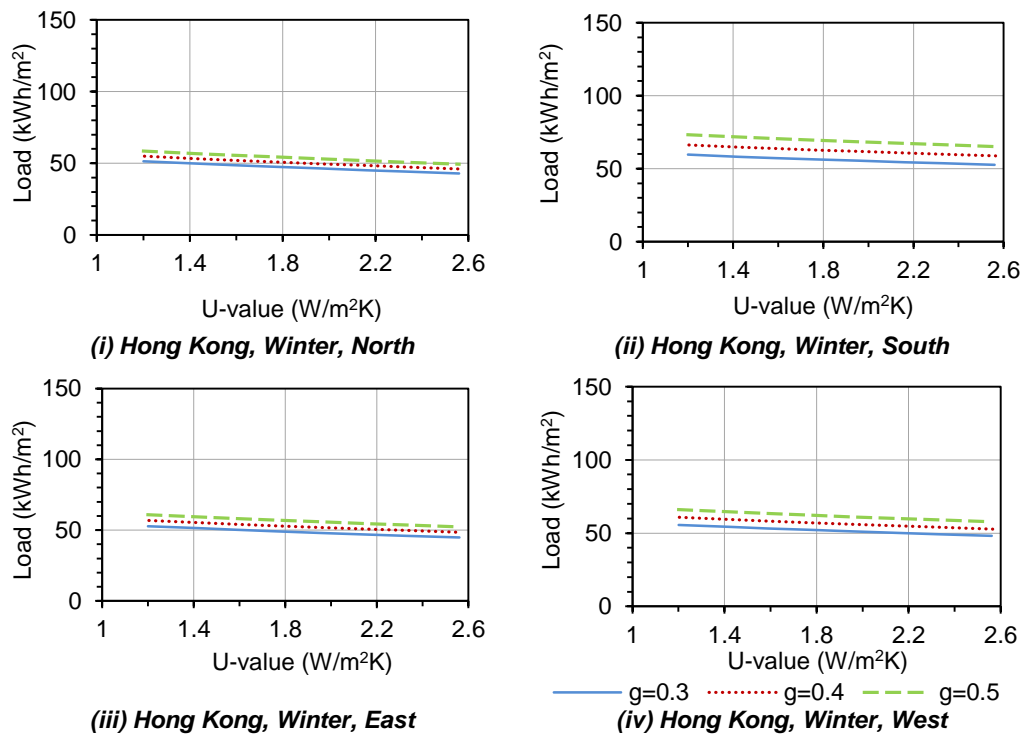


Figure 5.14 Effect of U and g-values and building orientation on cooling load of test office using Tas in winter, Hong Kong, SC2

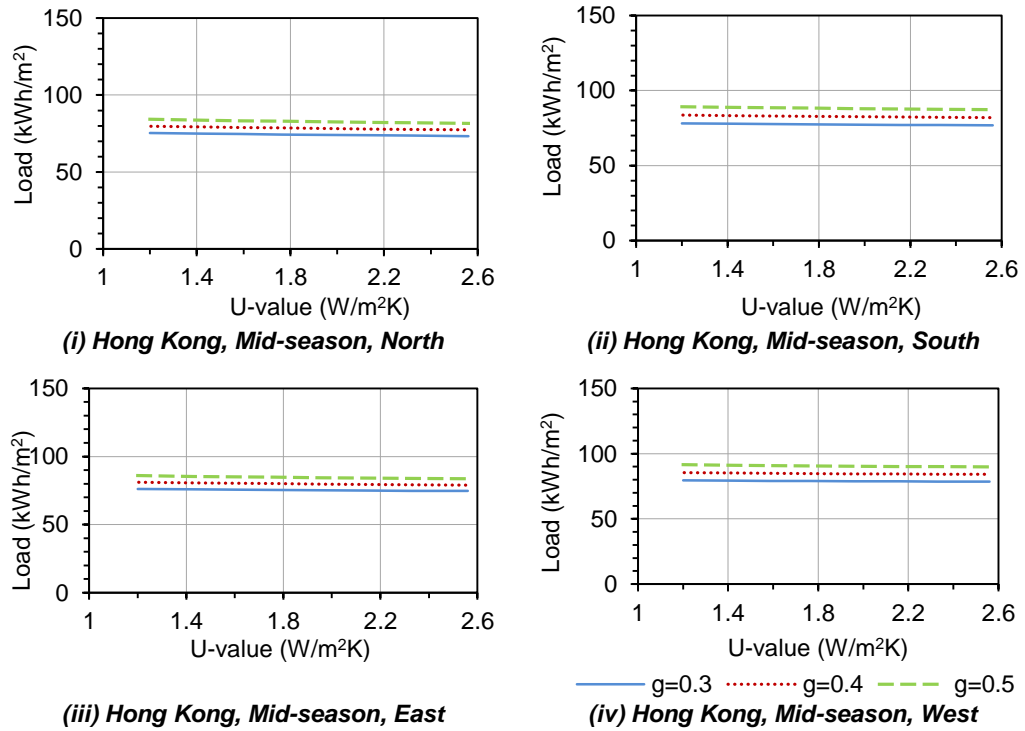


Figure 5.15 Effect of U and g-values and building orientation on cooling load of test office using Tas in mid-season, Hong Kong, SC2

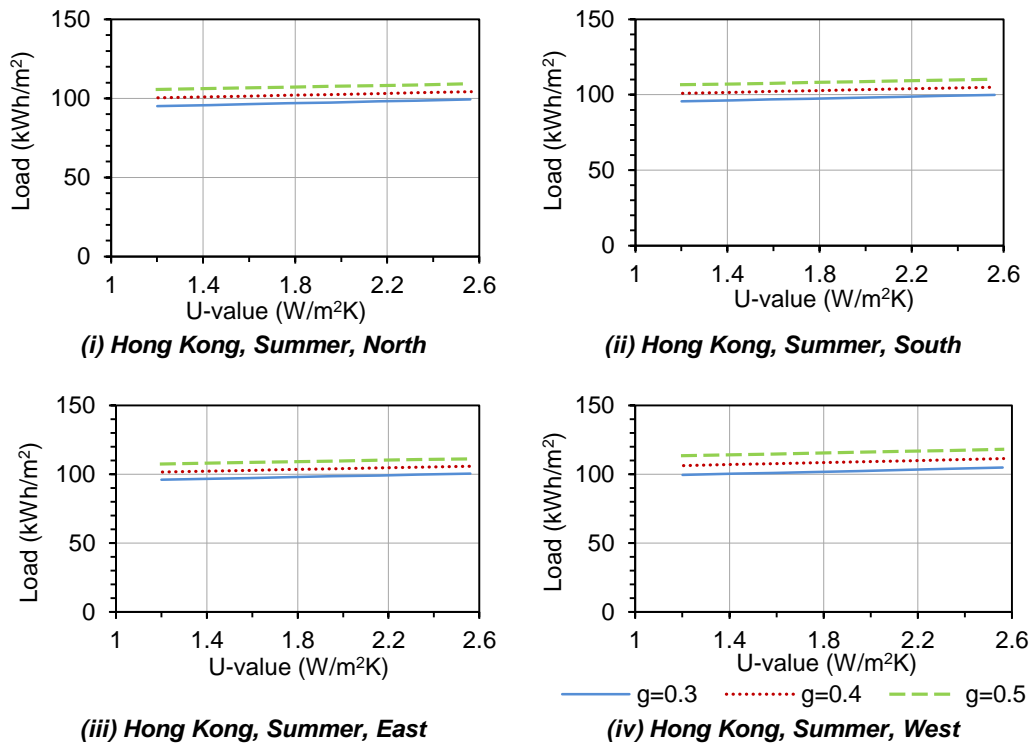


Figure 5.16 Effect of U and g-values and building orientation on cooling load of test office using Tas in summer, Hong Kong, SC2

Analysis of the heat balance equation parameters

The breakdown of the results for SC2 exhibits the same reasons for the variation in season patterns as for SC1. Table 5.10 shows the effect of lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ on the values for the principal terms by season, assuming $g = 0.5$. In winter, the provision of better-insulated facades decreases conduction heat losses, from 26kWh/m^2 to 17kWh/m^2 , which in turn increases the energy required for cooling from 65kWh/m^2 to 73kWh/m^2 .

During mid-season, the indoor and outdoor temperatures are virtually identical (Table 5.5) and this reduces both conduction and ventilation heat losses and increases cooling demand. This would be higher still were it not for the fact that during mid-season a South facing office experiences a reduction in solar irradiation, which reduces solar heat gain from 43 kWh/m^2 to 33 kWh/m^2 . From Table 5.10 it can also be seen that the provision of a low U-value facade has very little or no effect on the various factors influencing energy demand, and thereby the overall energy demand.

During summer, outdoor temperatures are on average around 3°C higher than indoors. From Table 5.10 it can be seen that, in the case of facades with a U-value of $2.6\text{Wm}^2/\text{K}$, this results in conductive heat gains, as well as heat gains from the ventilation. Using a facade with a lower U-value reduces conductive heat gains, which reduces the overall energy demand.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	0	73	-17	-15	65	43	-3
	2.6	0	65	-26	-15	65	43	-1
M	1.2	0	89	-8	-3	66	33	1
	2.6	0	87	-10	-3	66	33	1
S	1.2	0	107	0	8	66	31	2
	2.6	0	110	4	8	66	31	2

Table 5.10 Effect of U-value on energy demand of South-facing offices in Hong Kong assuming $g = 0.5$ using T_{as} , SC2

The major difference between SC1 and SC2 is due to the change in Q_{int} , which rises from 40kWh/m^2 to 66kWh/m^2 . The heat loss due to conduction in SC2 also increases due to longer building operation hours: -15kWh/m^2 , -2kWh/m^2 and 8kWh/m^2 for winter, mid-season and summer respectively, whereas the values are -9kWh/m^2 , -1kWh/m^2

and 5kWh/m² in SC1. Changes in conduction, ventilation and building heat transfer are small compared with changes in $Q_{int.}$. Overall, prolonging working hours from 10 to 16 causes a rise in cooling demand in all seasons.

Effect of g-value

From the annual results (Figure 5.13), it can be seen that facades with lower g-values have lower energy requirements in Hong Kong. Figure 5.14 to Figure 5.16 show that this is true for all office orientations and seasons. Table 5.11 shows the effect of the g-value on South-facing tested offices using a facade with a U value of 1.2W/m²K. Lowering the g-value of the facade from 0.5 to 0.3 can reduce the load in all seasons. It can also be seen in Table 5.11 that the energy demand falls with a reducing g-value, largely due to the decrease in solar gains. Lowering the facade g-value from 0.5 to 0.3, when $U = 1.2\text{W/m}^2\text{K}$ in a South-facing tested office, can reduce the cooling demand in winter, mid-season and summer by 13kWh/m², 11kWh/m² and 11kWh/m² respectively, and thereby reduce the annual energy demand by 35 kWh/m²; these figures are similar to those found in SC1.

	G	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	0	60	-13	-15	65	22	1
	0.4	0	66	-15	-15	65	33	-1
	0.5	0	73	-17	-15	65	43	-3
M	0.3	0	78	-5	-3	66	17	3
	0.4	0	84	-6	-3	66	25	2
	0.5	0	89	-8	-3	66	33	1
S	0.3	0	96	2	8	66	16	3
	0.4	0	101	1	8	66	23	3
	0.5	0	107	0	8	66	31	2

Table 5.11 Effect of g-value on energy demand of South-facing offices in Hong Kong assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC2

5.3 Effect of lowering internal gain, SC3

This section presents the Tas simulation results under the assumed SC3 condition. The total internal gains are assumed to be lower at 25W/m^2 , rather than 33.7W/m^2 as in SC1, using Hong Kong's current climate files.

5.3.1 Annual results, Tas

Figure 5.17 (i, ii, iii, iv) shows the effect of the U-value and g-value on annual energy demand of tested office obtained by means of Tas under the SC3 condition for North, South East and West-facing offices in Hong Kong. In general, reducing the internal heat gains from 33.7 to 25W/m^2 decreases the annual load from around $140\text{--}200\text{ kWh/m}^2$ (SC1, Figure 5.5) to 110 to 160 kWh/m^2 (SC3). Reducing the amount of internal heat gains does not affect the results observed in the annual load charts in SC3 compared with SC1. Lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ either increases the annual load in the tested offices by a very small amount or has no effect. However, lowering the g-value reduces the annual energy demand in the test offices by between 25 and 35 kWh/m^2 , depending on the orientation of the test offices.

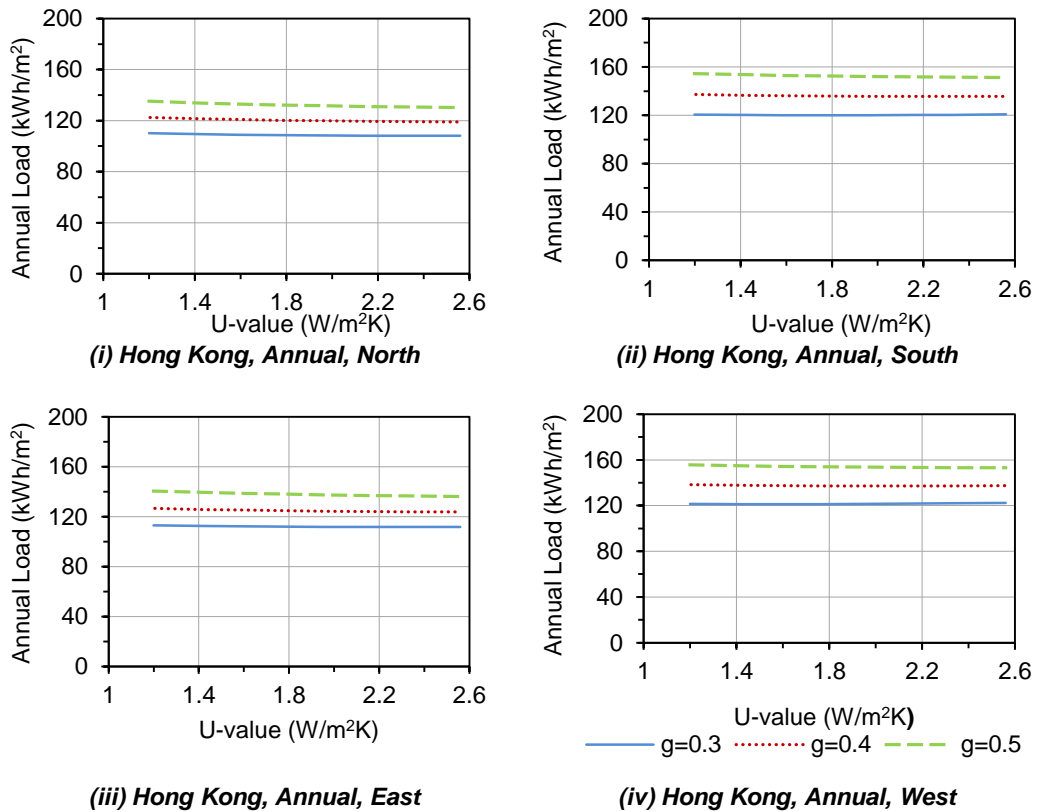


Figure 5.17 Effect of U and g values and building orientation on annual heating/cooling load of test office using Tas, Hong Kong, SC3

5.3.2 Seasonal trends, Tas

In order to understand the annual trends, the energy demand by season was determined. Figure 5.18, Figure 5.19 and Figure 5.20 show the energy required by offices facing all orientations in Hong Kong under SC3, in winter, mid-season and summer respectively. It was found that cooling load is needed all year round and there is no heating requirement. The amount of energy required by the tested offices in winter, mid-season and summer is lower than the corresponding seasonal energy requirements found in SC1 results. In SC1, the total load in the test offices ranges between 25kWh/m² and 60kWh/m² in winter, from 50kWh/m² to 70kWh/m² in mid-season and from 60kWh/m² to 90kWh/m² in the summer months; these values are 10kWh/m² to 40kWh/m², 30kWh/m² to 60kWh/m² and 50kWh/m² to 80kWh/m² for winter, mid-season and summer respectively in SC2.

It can be seen that the seasonal energy demand results under SC3 conditions have similar patterns to those in SC1. In winter, lowering a facade's U-value for the test offices leads to a slight increase in the cooling requirement. For mid-season, the impact of changing the U-value is negligible. In summer, the use of a facade with a lower U-value for the tested offices can reduce energy demand by a small amount. These results for all three seasons are found in offices facing all four orientations.

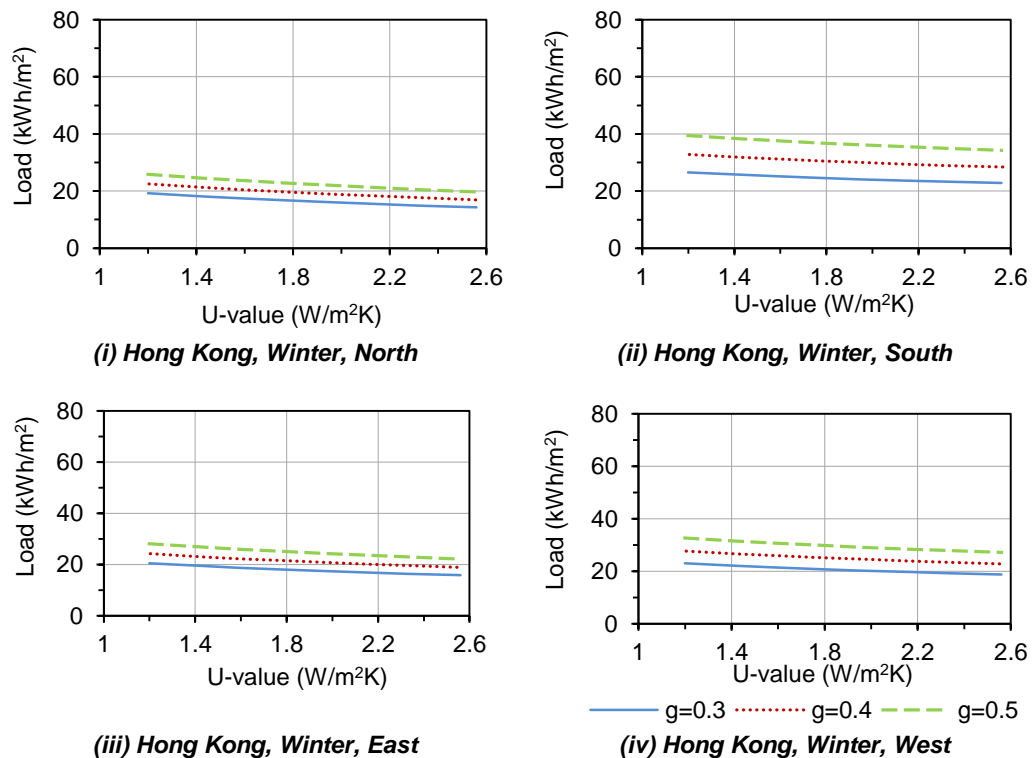


Figure 5.18 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Hong Kong, SC3

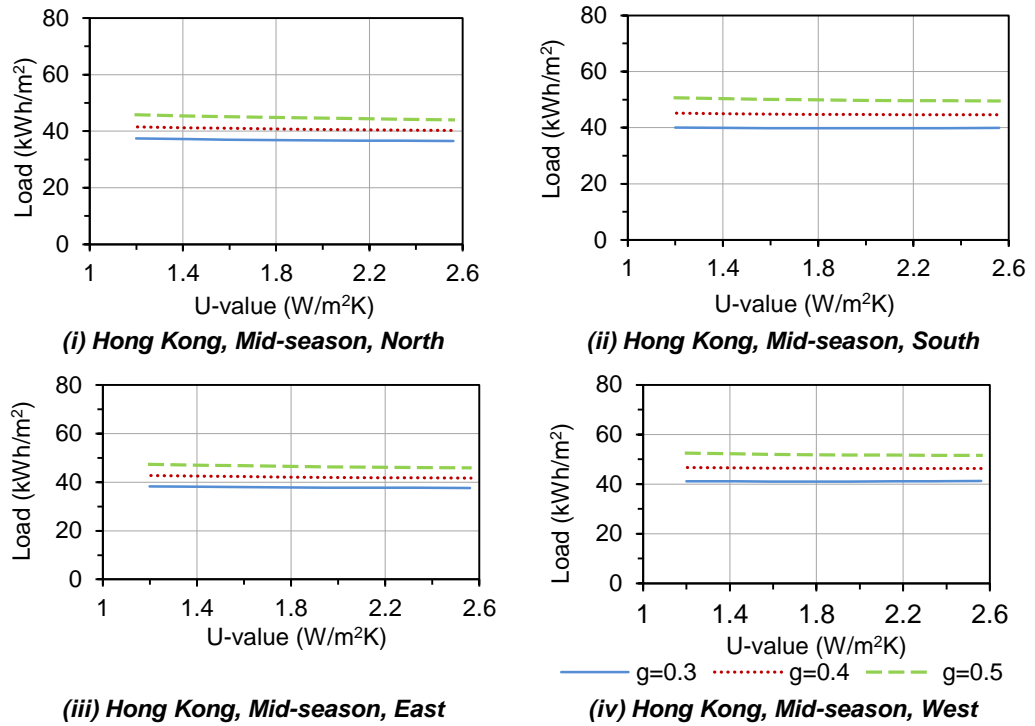


Figure 5.19 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Hong Kong, SC3

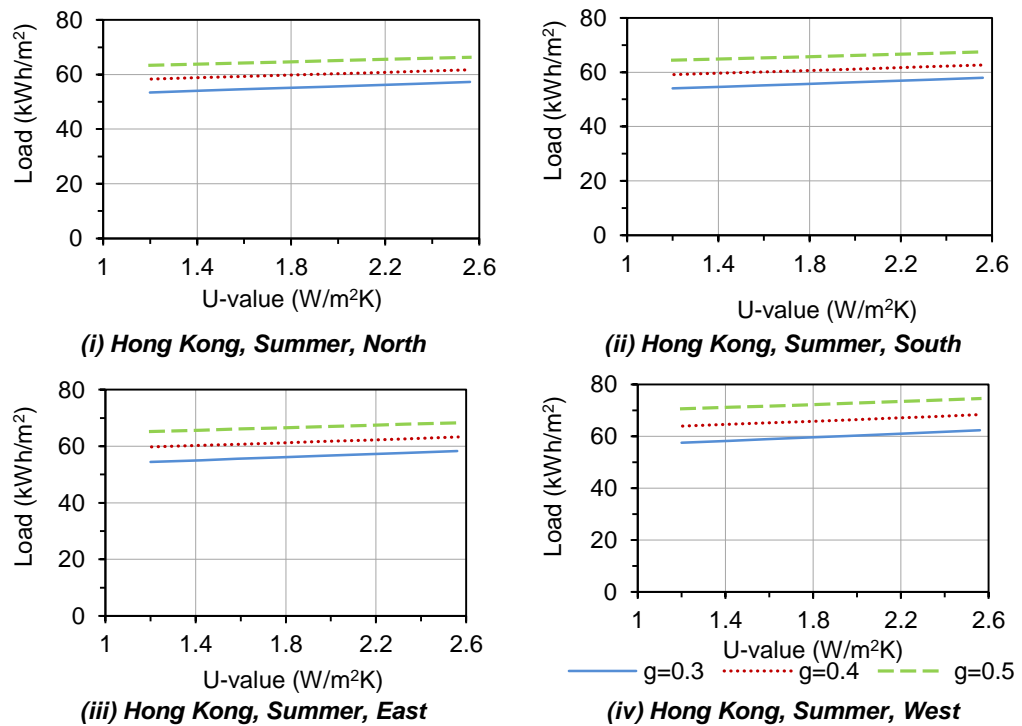


Figure 5.20 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in summer, Hong Kong, SC3

Breakdown of the results

Again, further insight are given by looking at the principal heat terms. Table 5.12 shows the results for South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and U is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. Table 5.12 shows that the difference between SC1 and SC3 results is due to the change in level of internal gains, Q_{int} , which are lowered from 40kWh/m^2 to 29kWh/m^2 . The effect of lowering the internal heat gain results in a lower cooling requirement in winter, mid-season and summer in the test offices, while the seasonal patterns remain the same. Changes in the conduction, ventilation and building heat transfer heat losses are negligible between SC1 and SC3.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	0	39	-16	-11	29	43	-6
	2.6	0	34	-23	-10	29	43	-4
M	1.2	0	51	-8	-2	29	33	-2
	2.6	0	49	-10	-2	29	33	-1
S	1.2	0	64	-1	7	29	31	-1
	2.6	0	68	2	7	29	31	-1

Table 5.12 Effect of U-value on energy demand of South-facing offices in Hong Kong assuming $g = 0.5$ using T_{as} , SC3

It can also be seen that the reasons behind the seasonal results are the same in SC1 and SC3. In winter, the provision of better-insulated facades decreases conduction heat losses, from 23kWh/m^2 to 16kWh/m^2 , which in turn increases the energy required for cooling from 34kWh/m^2 to 29kWh/m^2 . During mid-season, the indoor and outdoor temperatures are virtually identical (Table 5.5), and this reduces both conduction and ventilation heat losses and increases cooling demand. This would be higher still were it not for the fact that during mid-season South-facing office experience a reduction in solar irradiation, which reduces solar heat gain from 43kWh/m^2 to 33kWh/m^2 .

During summer, outdoor temperatures are on average around 3°C higher than indoors. In the case of facades with a U -value of $2.6\text{Wm}^2/\text{K}$ this results in conductive heat gains, as well as heat gains due to ventilation. However, the sun is at its weakest during this period and therefore heat gains due to solar radiation, Q_{sol} , are at their lowest. Using a facade with a lower U -value reduces conductive heat gains, which reduces overall

energy demand. It can also be seen that the provision of a low U-value facade has very little or no effect on the various factors influencing energy demand, and indeed the overall energy demand.

Effect of g-value

The g-value has a greater energy-saving effect than the U-value. From the annual results (Figure 5.17), it can be seen that facades with lower g-values have lower energy requirements in Hong Kong. From Figure 5.18 to Figure 5.20, this is also true for all office orientations and seasons. Table 5.13 shows the effect of the g-value on tested offices using a facade with a U-value of $1.2 \text{ W/m}^2\text{K}$ in South-facing test offices. Lowering the g-value of the facade from 0.5 to 0.3 can reduce the load in all seasons. The energy demand declines with a reducing g-value largely because of the decrease in solar gains. Lowering the facade's g-value from 0.5 to 0.3, when $U = 1.2 \text{ W/m}^2\text{K}$ in a South-facing test office, can reduce the cooling demand in winter, mid-season and summer, by 12 kWh/m^2 , 11 kWh/m^2 and 10 kWh/m^2 , and hence it cuts the annual energy demand by 33 kWh/m^2 . These figures are similar to those found in SC1. It should be noted that there is a small variation in the values of conduction heat gain, which might be thought to be constant within the same season for all three levels of g-value. The differences may be attributed to the calculation theory of Tas. However, the differences are not large and not discussed here.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	0	27	-12	-10	29	22	-2
	0.4	0	33	-14	-10	29	33	-4
	0.5	0	39	-16	-11	29	43	-6
M	0.3	0	40	-5	-2	29	17	0
	0.4	0	45	-6	-2	29	25	-1
	0.5	0	51	-8	-2	29	33	-2
S	0.3	0	54	2	7	29	16	1
	0.4	0	59	0	7	29	23	0
	0.5	0	64	-1	7	29	31	-1

Table 5.13 Effect of g-value on energy demand of South-facing offices in Hong Kong assuming $U = 1.2 \text{ W/m}^2\text{K}$ using Tas, SC3

5.4 Effect of climate change, SC4

This section investigates the effect of climate change on the energy performance of high-performance facades in offices in Hong Kong. The future climate file, which is the 2050 medium emission scenario, is used. The standard working hours scenario is assumed, 10 working hours per day, 7 days a week, with assumed internal gains of 33.7W/m^2 in the test offices. Test results from the Tas simulations for Hong Kong under a climate change scenario are presented and discussed.

Climate data

Table 5.14 shows the seasonal average values of hourly climate data used in the Tas simulations. Winter is the coldest time of the year, with the least amount of solar irradiance, whereas summer is the hottest time, with the greatest solar irradiance. The indoor design temperature has been set as 21°C to 25°C . Compared with Hong Kong's current scenario, the seasonal average temperatures increase by 2.2°C , 1.7°C and 1.5°C for winter, mid-season and summer respectively. Additionally, solar irradiance also increases by 78kWh/m^2 in winter and 178kWh/m^2 in mid-season, and falls by 380kWh/m^2 summer.

Hong Kong	$T_{\max} (^\circ\text{C})$	$T_{\min} (^\circ\text{C})$	$T_{\text{av}} (^\circ\text{C})$	$S (\text{kWh/m}^2)$
Winter	25.5	15.7	19.6	3,848.5
Mid-season	30.0	19.9	24.9	3,830.5
Summer	33.4	25.9	29.7	4,485.0

Table 5.14 Seasonal average temperature and solar radiation data for Hong Kong, Tas, 2050

5.5.1 Annual results for Hong Kong, Tas

Figure 5.21 (i, ii, iii, iv) shows the effect of the U-value and g-value on annual energy demand obtained from Tas simulations in SC4, for offices tested in Hong Kong for North, South, East and West orientations. In general, the annual loads in the test offices are higher under the SC4 condition; the annual load in the test offices increases from around $140\text{--}200 \text{ kWh/m}^2$ (SC1, Figure 5.5) to $160\text{--}210 \text{ kWh/m}^2$ (SC4). It can be seen that lowering the U-value has a marginal effect on the energy demand. Unlike the trends found in SC1, lowering the U-value does not show an increase in the annual energy demand of the tested offices. Lowering the g-value from 0.5 to 0.3 is still beneficial: it can reduce energy demand of the tested offices, irrespective of the U-value and orientation. The effect is most obvious in South-facing tested offices.

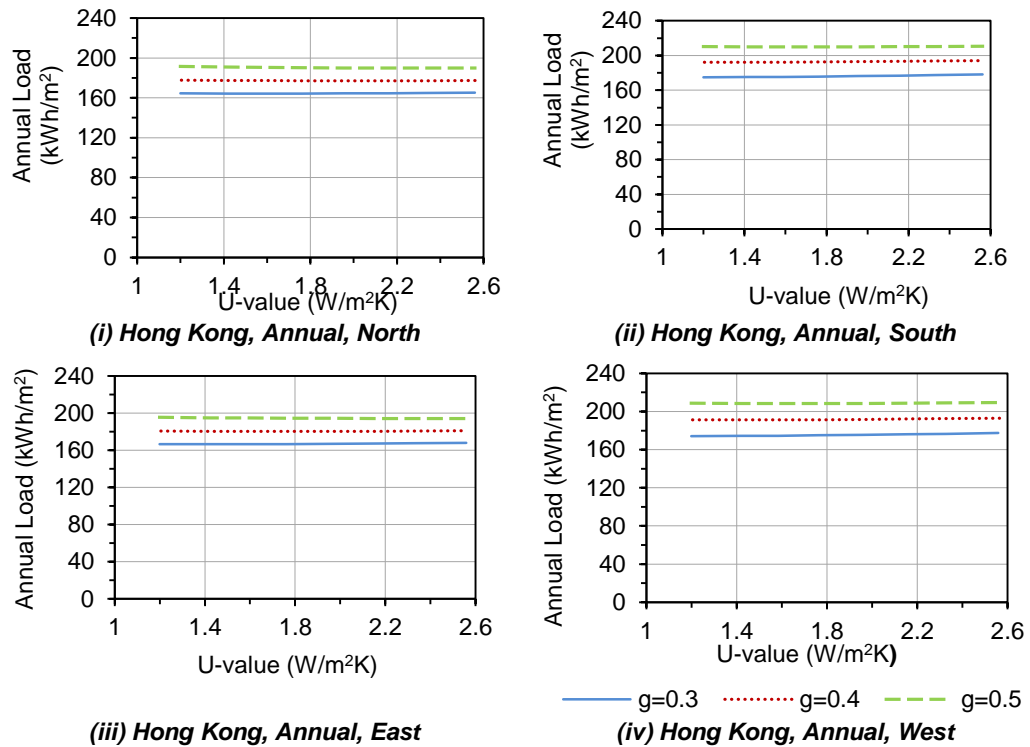


Figure 5.21 Effect of U and g-values and building orientation on annual heating/cooling load of test office using Tas, Hong Kong, SC4

5.5.2 Seasonal results of Hong Kong from Tas

In order to understand the annual trends, the energy demand by season was determined. Figure 5.22 to Figure 5.24 show the energy required by offices facing all orientations in Hong Kong under SC4, in winter, mid-season and summer respectively. It is found that a cooling load is needed all year round and there is no heating requirement. The influence of the U-value on the seasonal energy demand is similar under SC4 conditions and SC1. In winter, lowering a facade's U-value in the tested offices leads to a slight increase in energy demand. In mid-season, the impact of changing the U-value is negligible. In summer, the use of a facade with a low U-value in the test offices can reduce the energy demand by a small amount.

Under the future climate condition (SC4), the energy required in the tested offices in winter, mid-season and summer is generally higher than in SC1. Cooling requirements are lowest in winter, with a range between 30kWh/m² to 60kWh/m², in mid-season between 50kWh/m² to 80kWh/m², and 70kWh/m² to 100kWh/m² in summer. Under the SC1 condition, they are 25kWh/m² to 60kWh/m² in winter; 50kWh/m² to 70kWh/m² in mid-season, and 60kWh/m² to 90kWh/m² in summer.

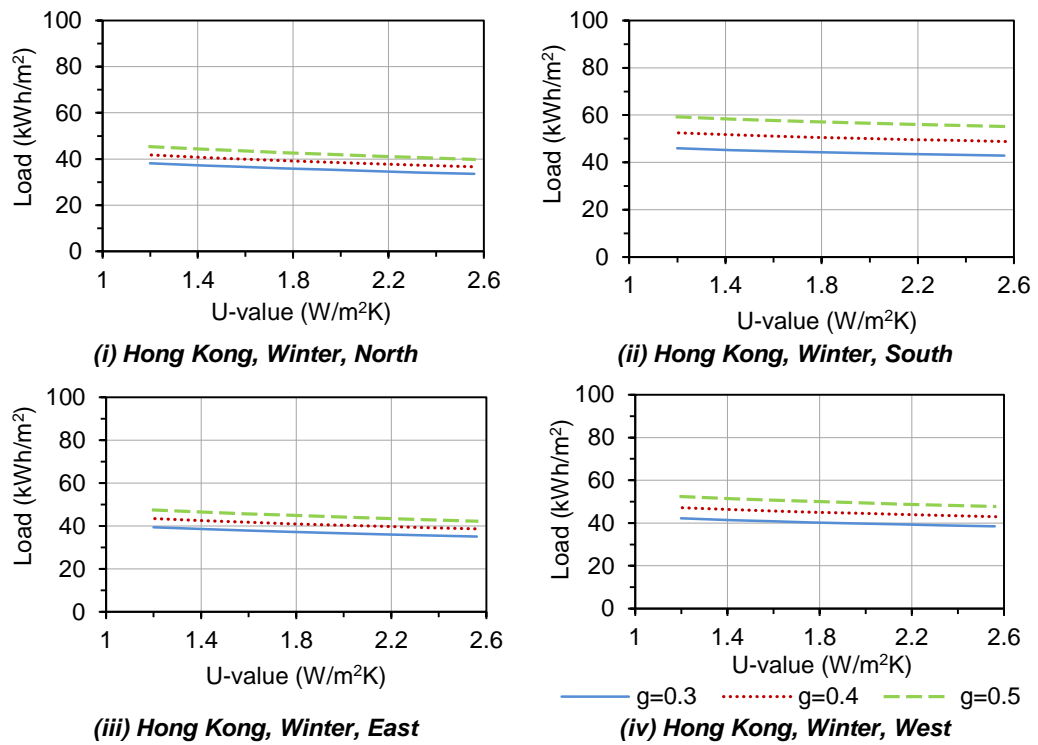


Figure 5.22 Effect of U and g-values and building orientation on cooling load of test office using Tas in winter, Hong Kong, SC4

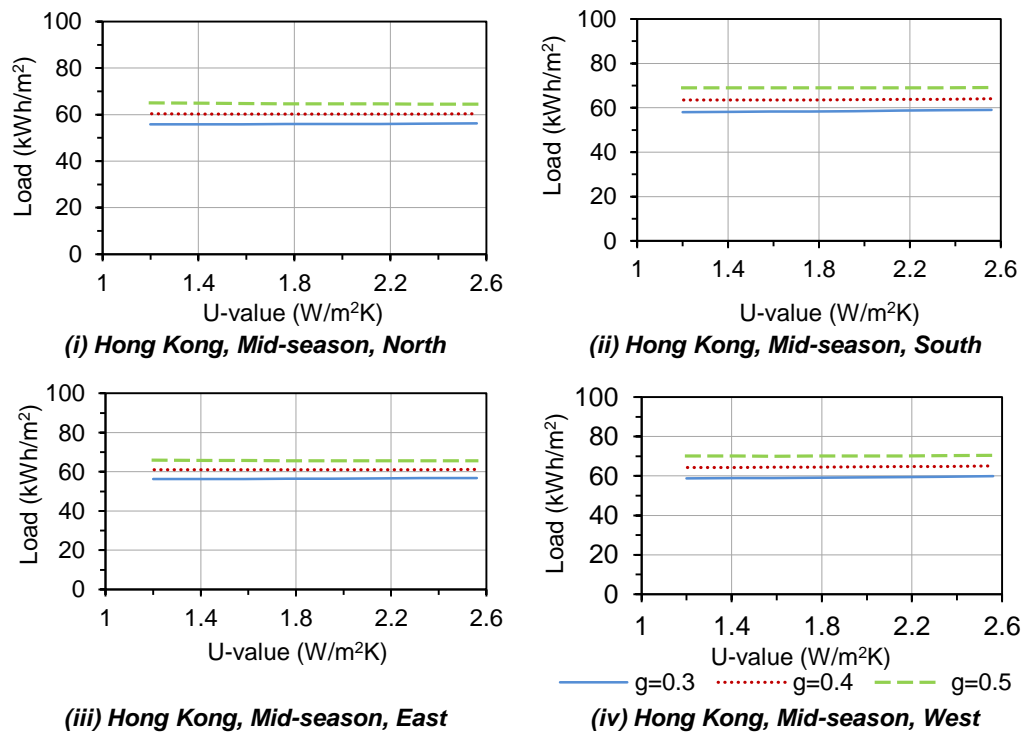


Figure 5.23 Effect of U and g-values and building orientation on cooling load of test office using Tas in mid-season, Hong Kong, SC4

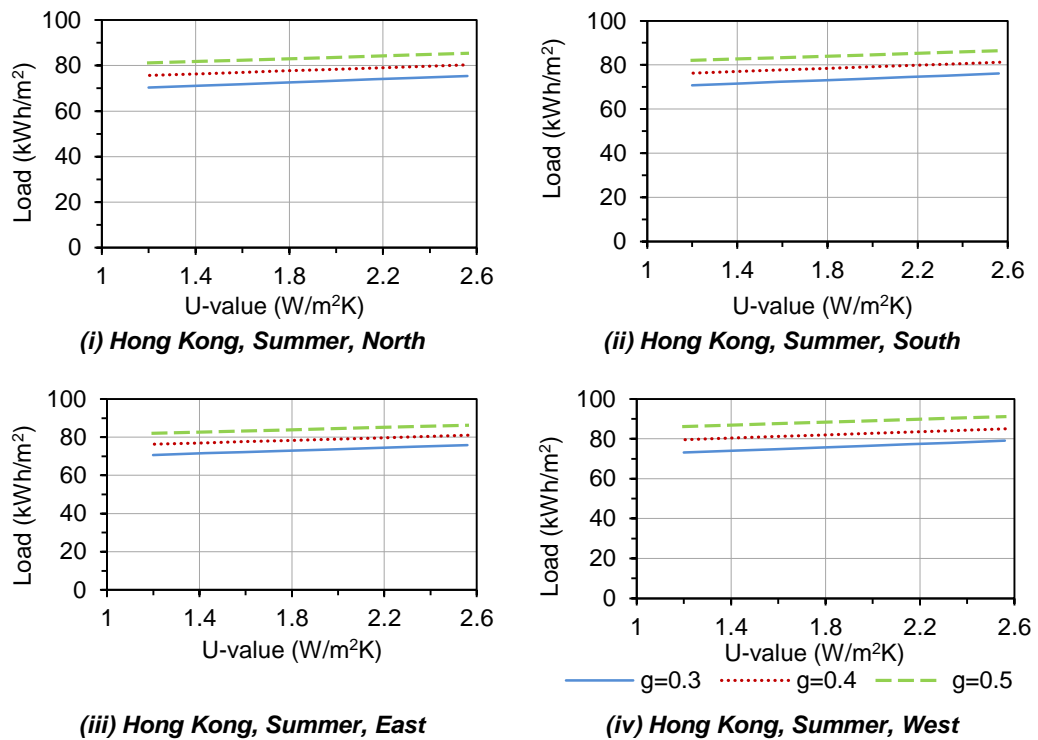


Figure 5.24 Effect of U and g-values and building orientation on cooling load of test office using Tas in summer, Hong Kong, SC4

Breakdown of the results

Table 5.15 shows the effect of lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ on the values for the principal terms by season, assuming $g = 0.5$ and with the indoor design temperature set at 21 to 25°C .

It can be seen in Table 5.15 that the effect of the temperature rise in winter, mid-season and summer results in a lower heat loss due to conduction and ventilation in winter and mid-season. As the average outdoor temperature is higher in summer, a lower U-value facade reduces the unwanted heat gain due to conduction, and the value for Q_{int} stays the same. Therefore, the overall effect of the rise in temperature is that the test offices require more cooling. However, this does not change the effect of lowering the U-value of the facade on the energy required by test offices in winter, mid-season and summer.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	0	59	-14	-6	40	44	-5
	2.6	0	55	-20	-6	40	44	-3
M	1.2	0	69	-6	1	41	34	-1
	2.6	0	69	-7	1	41	34	-1
S	1.2	0	82	0	8	41	33	0
	2.6	0	86	5	8	41	33	-1

Table 5.15 Effect of U-value on energy demand of South-facing offices in Hong Kong assuming $g = 0.5$ using Tas, SC4

In winter, the provision of better-insulated facades decreases conduction heat losses, from 20 kWh/m^2 to 14 kWh/m^2 which in turn increases the energy required for cooling from 55 kWh/m^2 to 59 kWh/m^2 . During mid-season, the indoor and outdoor temperatures are virtually identical (Table 5.5); this reduces both conduction and ventilation heat losses and increases cooling demand. This would be higher still were it not for the fact that during mid-season a South-facing office experiences a reduction in solar irradiation, which reduces the solar heat gain from 44 kWh/m^2 to 34 kWh/m^2 .

During summer, outdoor temperatures are on average around 3°C higher than indoors, which causes heat gains from conduction and ventilation; in the case of facades with a U-value of $2.6 \text{ Wm}^2/\text{K}$, this results in conductive heat gains, as well as heat gains due to ventilation. However, the sun is at its weakest during this period and therefore Q_{sol} , are at their lowest. Despite this being the case, the energy demand is higher in summer than at mid-season. Using a facade with a lower U-value reduces conductive heat gains, which reduces the overall energy demand. A lower U-value facade does have a greater energy-saving effect in summer because of the rise in outdoor temperature, but the amount is insignificant. From Table 5.15 it can also be seen that the provision of a low U-value facade has very little or no effect on the overall energy demand.

Effect of g-value

Table 5.16 shows the effect of the g-value on tested offices facing South, using a facade with a U value of $1.2 \text{ W/m}^2\text{K}$. Energy demand falls with a reducing g-value, largely because of the decrease in solar gains. Lowering the facade g-value from 0.5 to 0.3, when $U = 1.2 \text{ W/m}^2\text{K}$ in South-facing tested offices, can reduce the cooling demand by 13 kWh/m^2 , 11 kWh/m^2 and 11 kWh/m^2 in winter, mid-season and summer respectively, and hence lower annual energy demand by 35 kWh/m^2 ; these figures are similar to those found in SC1.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0	46	-10	-6	40	23	-1	0
	0	52	-12	-6	40	33	-3	0
	0	59	-14	-6	40	44	-5	0
M	0	58	-3	1	41	18	1	0
	0	63	-5	1	41	26	0	0
	0	69	-6	1	41	34	-1	0
S	0	71	3	8	41	17	1	0
	0	76	2	8	41	25	0	0
	0	82	0	8	41	33	0	0

Table 5.16 Effect of g-value on energy demand of South-facing offices in Hong Kong assuming $U = 1.2 \text{ W/m}^2\text{K}$ using Tas, SC4

5.5 Summary and conclusions

The effect of a facade's U-value and g-value has been assessed in tested offices facing North, East, West and South under four scenarios. SC1 is the normal working hours scenario, SC2 is prolonged working hours, SC3 is lower internal gains and SC4 is the scenario where climate change is considered.

5.5.1 Results summary

The numerical results used to produce the annual energy demand figures for the four tested scenarios are presented in Table 5.17. The effect of lowering the U-value from 2.6 to $1.2 \text{ W/m}^2\text{K}$ was also calculated and is included in the table.

		SC1				SC2				SC3				SC4			
	U	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
g=0.3	1.20	148	151	159	160	222	225	233	235	110	113	121	122	164	166	175	174
	1.43	147	150	158	159	220	224	232	234	109	113	120	121	164	166	175	174
	1.59	146	150	158	159	220	223	232	233	109	112	120	121	164	167	175	175
	1.77	146	149	157	159	219	223	231	233	109	112	120	121	164	167	176	175
	1.96	145	149	157	158	218	222	231	232	108	112	120	121	164	167	176	176
	2.16	145	148	157	158	217	221	230	232	108	112	120	122	165	167	177	176
	2.33	144	148	157	158	216	221	230	232	108	112	120	122	165	167	177	177
	2.56	144	148	157	159	216	220	229	232	108	112	121	122	165	168	178	177
	2.6-1.2	-4	-3	-2	-1	-6	-5	-4	-3	-2	-1	0	1	1	1	3	3
g=0.4	1.20	160	165	175	176	235	240	251	253	122	127	137	138	178	181	192	191
	1.43	159	163	174	176	233	238	250	252	121	126	137	138	177	180	192	191
	1.59	158	163	174	175	232	237	249	251	121	125	136	137	177	180	192	191
	1.77	158	162	173	175	231	236	248	250	120	125	136	137	177	180	193	191
	1.96	157	161	173	174	230	236	248	250	120	124	136	137	177	180	193	192
	2.16	156	161	173	174	229	235	247	249	119	124	136	137	177	180	193	192
	2.33	156	161	172	174	229	234	246	249	119	124	136	137	177	181	194	192
	2.56	155	160	172	174	228	233	246	248	119	124	136	137	177	181	194	193
	2.6-1.2	-5	-4	-3	-2	-7	-6	-5	-4	-4	-3	-2	-1	-1	0	2	2
g=0.5	1.20	173	179	193	194	248	254	269	271	135	141	154	156	192	195	210	209
	1.43	172	177	191	193	247	253	268	270	134	139	154	155	191	195	210	208
	1.59	171	176	191	192	246	252	267	269	133	139	153	154	191	195	210	208
	1.77	170	176	190	191	244	251	266	268	132	138	152	154	190	194	210	208
	1.96	169	175	189	191	243	250	265	267	132	138	152	154	190	194	210	209
	2.16	168	174	189	190	242	249	264	267	131	137	152	153	190	194	210	209
	2.33	167	173	188	190	241	248	264	266	131	137	151	153	190	194	210	209
	2.56	166	173	188	190	240	247	263	266	130	136	151	153	190	194	211	209
	2.6-1.2	-7	-6	-5	-4	-8	-7	-6	-5	-5	-4	-3	-2	-2	-1	0	1

Table 5.17 Effect of U-value and g-value on annual load, Hong Kong, Tas

It can be seen that lowering the U-value of the facade in Hong Kong offices does not reduce the annual cooling demand. With changes such as an unexpected prolongation of working hours or a lower level of internal gains, lowering the U-value of facades still increases the annual cooling requirement. The effect of lowering the U-value is worse when the working hours are longer but the effect is better in the lower internal gain condition. In the projected Hong Kong future climate scenario, 2050, lowering a facade's U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ shows some positive effect on the energy demand in all of the test offices. In some cases it can reduce the energy demand by 3kWh/m^2 .

Lowering the g-value of the facade has a more significant effect in reducing the cooling demand, and it remains similar as the conditions change. The results also suggest that using a low g-value facade is beneficial in all four test scenarios, and lowering the g-value from 0.5 to 0.3 reduces the annual cooling requirements in test offices facing North, East, South and West by 28kWh/m^2 , 29kWh/m^2 , 35kWh/m^2 and 35kWh/m^2 respectively. These values remain almost the same with changing U-values and varied internal and external condition tested.

In general, the total annual loads are higher in SC2 than in SC1 because of the longer working hours. The annual energy demand of the test office decreases by around 25% in SC3 where there is less internal heat gains. The climate change causes around 10% increase in the annual cooling requirements. Hence, focusing on reducing the g-value of the facade and internal heat gains in Hong Kong and in places with similar climate conditions is recommended.

5.5.2 Conclusions

1. When outdoor temperatures are higher than those indoors low U-value facades can reduce the energy required for cooling in office buildings.
2. In Hong Kong, however, since average outdoor temperatures are just a few degrees higher than the design indoor value only during summer, the savings in energy derived by using low U-value facades are relatively modest and negated by performances at other times of the year when average outdoor temperatures are very similar or lower than design indoor values and overall result in a net increase in energy demand.
3. Longer occupancy hours increase energy usage and the use of low U-value facades exacerbates this condition.
4. Climate change may favour the use of low U-value facades because of generally higher outdoor temperatures. Nevertheless the benefits appear to be marginal and probably not worth the extra expenditure involved in installing low U-value facades.
5. Cooling is necessary at all times of the year in Hong Kong including winter because of high internal and solar gains.
6. The highest energy demand occurs in summer and the lowest in winter. Except for south facing offices this pattern of energy demand coincides with the pattern of solar radiation and maximises the possibility of sourcing the energy necessary for cooling of offices in Hong Kong from solar power.
7. Low g-value facades can reduce energy usage by up to 25% which is comparable with the energy savings possible by using equipment and lighting with lower internal gains.

CHAPTER 6 INFLUENCE OF HIGH-PERFORMANCE FACADES ON ENERGY USAGE IN CARIBOU OFFICES

Introduction

This chapter investigates the influence of high-performance facades on energy usage in office buildings in Caribou. Four scenarios are considered: standard working hour scenario (SC1), prolonged work hours scenario (SC2), lower internal gains scenario (SC3), and scenario 4 (SC4), which assumes that the weather conditions predicted for 2050 apply. For SC1 and SC2, preliminary tests using a steady-state method are carried out alongside the Tas simulation, in order to ensure that the results obtained from Tas are reasonable.

Hence, results from the steady-state method are presented first, followed by Tas results for SC1 and SC2. For SC3 and SC4, only Tas simulations were performed. In each case, the heating/cooling load is calculated assuming the use of facades with U-values which vary between 1.2W/m²K to 2.6W/m²K, with g-values which vary between 0.3 and 0.5. All tests are carried out on offices facing North, East, South and West. Table 6.1 summarises the test programme for Caribou.

Fixed conditions							
Test location: Caribou Ventilation rate:10 litres per person per second (l/p/s) WWR = 0.7 Indoor temperature: 21°C							
Test variables and methods							
Code	U-value (W/m ² K)	G-value	Orientation s	Working schedule	Internal gains (W/m ²)	Weather (CIBSE)	Modelling tools
SC1	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10hrs)	33.7	Current	Steady state, Tas
SC2	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0700-2300 (16hrs)	33.7	Current	Steady state, Tas
SC3	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10hrs)	25	Current	Tas
SC4	1.2 – 2.6	0.3, 0.4, 0.5	N, S, E, W	0800-1800 (10hrs)	33.7	Future, 2050	Tas

Table 6.1 Test summary for Caribou

Similarly, for each scenario, four types of results are included. Annual results are presented first. These show the influence of U and g-values on annual energy demand of offices facing North, South, East or West. Following this, results showing the effect of U and g-values on total seasonal energy demand, as well as seasonal heating and cooling loads, are provided. Further insights are provided by presenting the numerical values of the principal factors influencing the energy demand. At the end of the chapter, a summary table of numerical results used to produce the annual charts is provided, in order to quantify the effect of the U and g-values and for ease of comparison.

6.1 Influence of high-performance facades, SC1

This section shows the test results for Caribou, assuming the standard working hours scenario (SC1). The test results from the steady-state method are presented and discussed first, followed by the more detailed and accurate results obtained from Tas.

6.1.1 Steady-state study

Climate data

Table 6.2 shows the seasonal average values of outdoor dry-bulb temperature, T_{out} , design indoor temperature, T_{in} , the average temperature difference between indoors and outdoors, ΔT , as well as solar irradiance values for North, South, East and West orientations, S_o . As previously noted, winter covers the period November-February, summer the period June-September and the remaining months are classed as mid-season. The monthly values are used to calculate the seasonal average temperatures and solar irradiance values.

It can be seen that in Caribou, the largest temperature difference occurs in winter -29.6°C , and the smallest temperature difference is in summer, -5.1°C . The average outdoor temperature is always lower than the design indoor temperature, as indicated by the negative ΔT values. Additionally, apart from South orientation, winter months experience the least amount of solar heat gains, whereas summer sees the most. South-facing facades receive the most solar irradiance in mid-season, which is different from the rest of the orientations. The value of the solar irradiance on a North-facing facade is the lowest, whereas it is the highest on a South-facing facade. The solar irradiance values for East and West-facing facades are similar.

$^{\circ}\text{C}$	T_{out}	T_{in}	ΔT	$S_o, (\text{W/m}^2)$			
				N	E	S	W
Winter	-8.6	21	-29.6	24.0	51.3	119.6	49.6
Mid-seasons	4.0	21	-17.0	52.9	104.2	132.4	101.5
Summer	15.9	21	-5.1	66.4	123.6	123.6	121.6

Table 6.2 Caribou indoor and outdoor temperatures ($^{\circ}\text{C}$), solar irradiance (W/m^2), averaged by seasons

Annual results

Figure 6.1 (i, ii, iii, iv) shows the effect of U and g-values on annual energy demand in offices facing North, South, East and West, respectively, in Caribou under SC1. It can be seen that utilising lower U-value facades can reduce the annual energy demand in all offices apart from the case where $g = 0.5$ for a South-facing office. The energy-saving effect of reducing the U-value of facades depends on the g-value of the facade; it is most beneficial when $g = 0.3$. On the other hand, lowering the g-value of the facades does not have much effect in North-facing offices, and it can reduce the annual energy demand when the U-value is lower in the offices with other orientations.

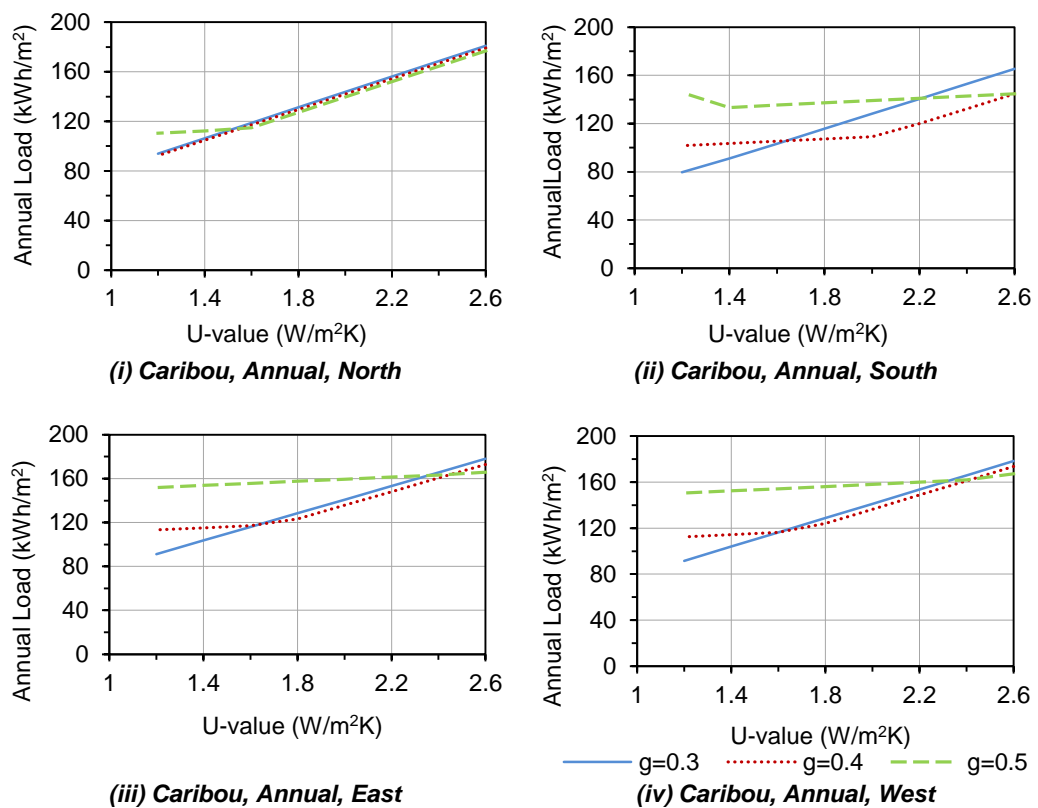


Figure 6.1 Effect of U and g-values and building orientation on annual heating/cooling load of test office using steady-state calculation, Caribou, SC1

Seasonal Caribou results, steady-state

In order to understand these trends, seasonal energy demand patterns were investigated. Figure 6.2 to Figure 6.4 show the heating/cooling loads estimated using the steady-state method for Caribou in winter, mid-season and summer, respectively. A positive number in the figure indicates that there is an overall net heat gain, representing the amount of cooling load. Conversely, a negative number indicates an overall net heat loss, giving the amount of heating load. Both loads are given in kWh/m².

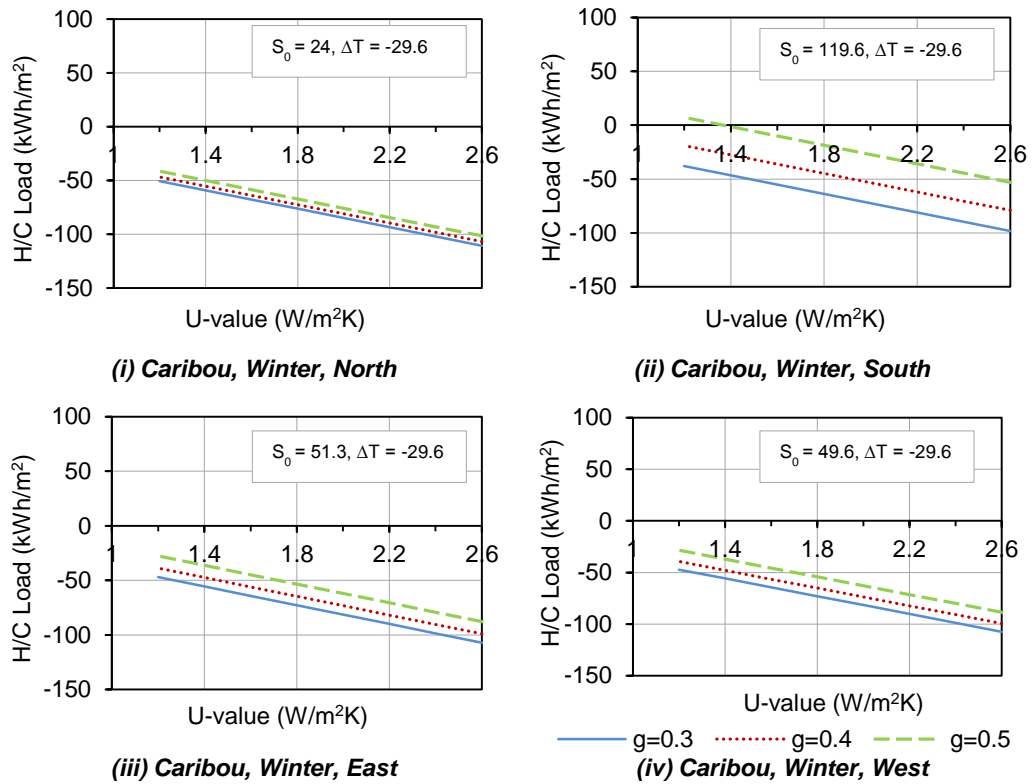


Figure 6.2 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in winter, Caribou, SC1

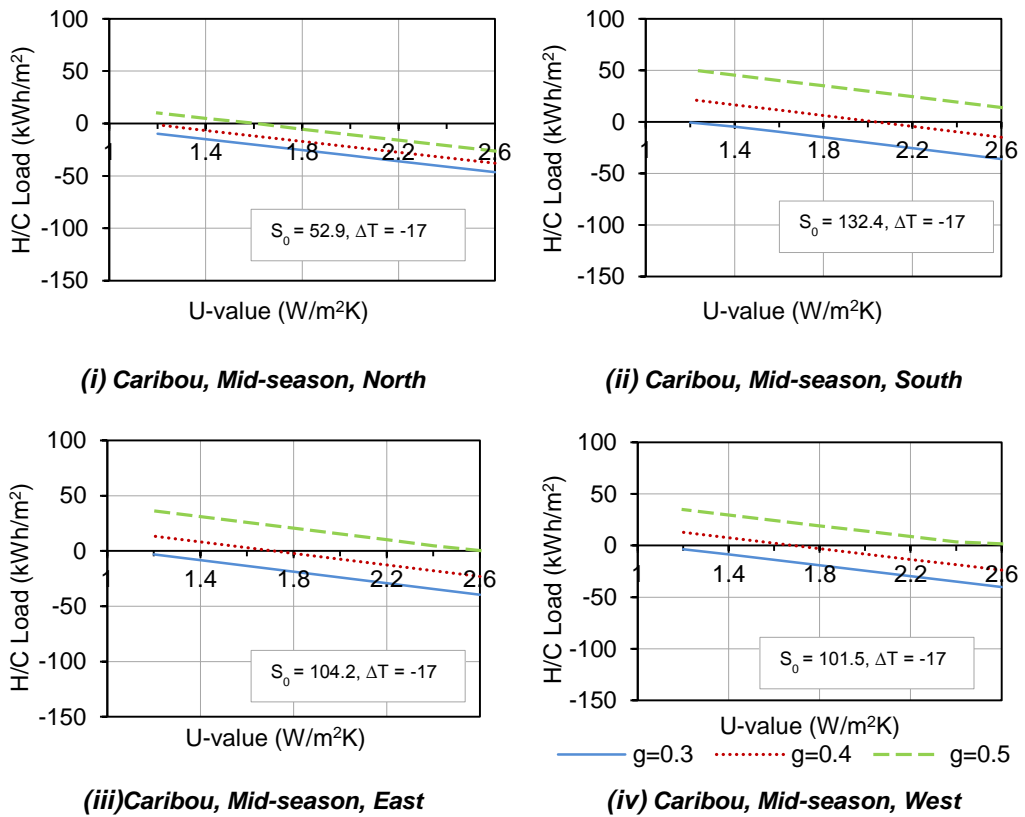


Figure 6.3 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in mid-season, Caribou, SC1

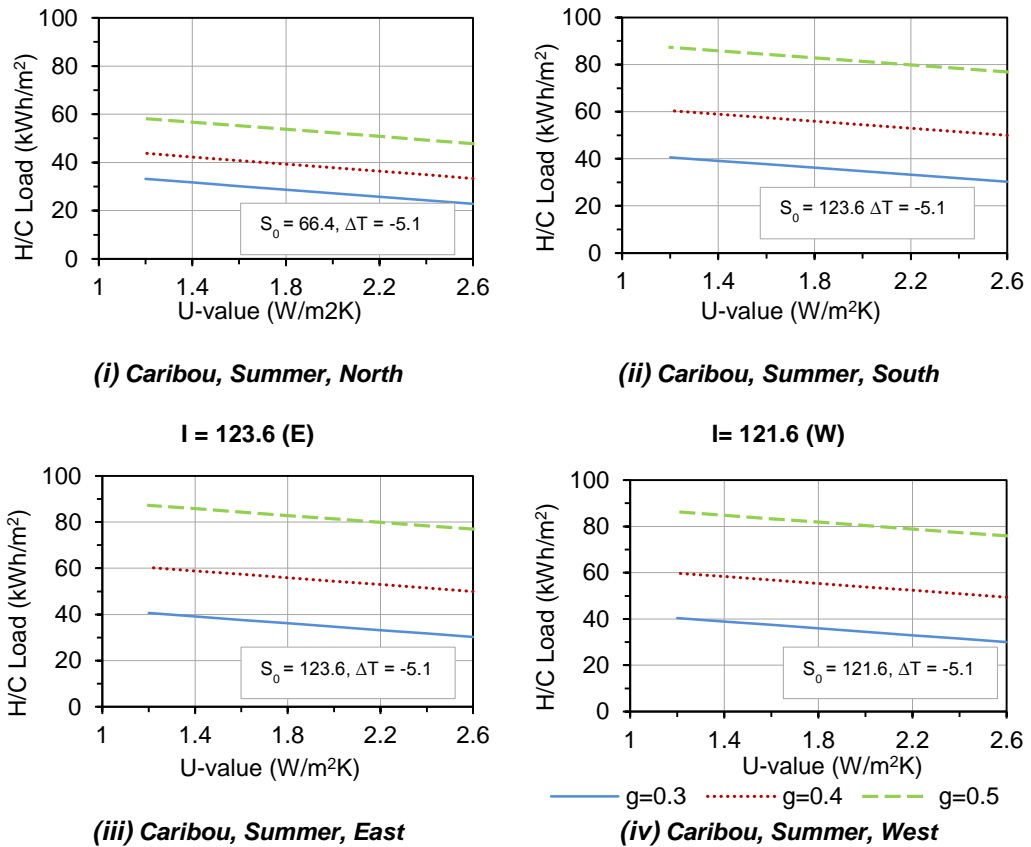


Figure 6.4 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in summer, Caribou, SC1

It can be seen that the effect of lowering the U-value and g-value is different in the three seasons. During winter (Figure 6.2), using facades with lower U-values can significantly reduce the total heat loss, and hence the heating demand of the test, offices irrespective of orientation. One exception is when $g = 0.5$ and $U = 1.4 \text{ W/m}^2\text{K}$ in South-facing offices, where the solar irradiance is a lot higher than for the other three orientations. A near-zero heating demand point can be observed at South orientation with a U-value of $1.4 \text{ W/m}^2\text{K}$ and a g-value of 0.5 . Cooling is required when the U-value is reduced below $1.4 \text{ W/m}^2\text{K}$. In mid-season, the weather is warmer, with $\Delta T = -17.4 \text{ }^\circ\text{C}$, and there is a higher level of solar irradiation, which is the highest in South-facing offices. It can be seen that there is a mix of heating and cooling loads in all offices. A few 'points of inflexion' can be observed: lowering the U-values is beneficial. In summer, all test offices only have cooling requirements, which are higher in offices that receive more solar heat gains and increase with decreasing U-value. Lowering the g-value of the facades is beneficial when there is an overall cooling demand, i.e. summer and some cases in mid-season, whereas it increases the energy demand in the rest of year, i.e. winter and some cases in mid-season.

Breakdown of the results

Further insights are obtained by considering the values of the principal factors influencing energy demand, namely:

- Conduction heat gain/loss through facade (Q_{cond})
- Ventilation heat gain/loss (Q_{air})
- Internal heat gain (Q_{int})
- Solar heat gain (Q_{sol})

Table 6.3 shows the results for North and South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and the U-value is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. A negative number indicates that there is heat loss or a heating demand, and vice versa.

It can be seen that heat loss due to conduction (Q_{cond}) and ventilation (Q_{air}) accounts for a large proportion of the total heat transfer in winter in Caribou, due to the large average indoor vs. outdoor temperature difference (ΔT), $-29.4\text{ }^\circ\text{C}$. Utilising facades with a lower U-value can reduce a significant amount of Q_{cond} during the heating season. For example, in a North-facing office, reducing the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ can reduce the heat loss, as well as the total heating demand, by 61kWh/m^2 . In a South-facing office, where the solar heat gain (Q_{sol}) is higher, lowering the U-value gives rise to 7kWh/m^2 of cooling load in the test office, rather than having $53\text{W/m}^2\text{K}$ of heat demand.

During mid-season, ΔT reduces to -17°C , hence the amount of heat losses due to conduction and ventilation is lower than that in winter, however the Q_{sol} increases. In North-facing office, lowering the U-value reduces the amount of conduction heat loss, which causes the office to have 10kWh/m^2 of cooling demand, rather than 27kWh/m^2 of heating demand.

However, lowering the U-value has a negative effect in South-facing offices mid-season and in all offices in summer, when there is either a higher amount of Q_{sol} or a smaller ΔT , which is $-5.1\text{ }^\circ\text{C}$ in summer. In these cases, there is a net heat gain, and good insulation unfavourably reduces Q_{cond} and increases the cooling demand. Overall, lowering the U-value reduces the annual energy demand by 66kWh/m^2 in North-facing offices because it can significantly reduce the heating requirement in winter. It does not have much effect on the annual energy demand in a South-facing office: although it reduces the heating demand in winter, it causes a large increase in the cooling demand in mid-season and summer. The difference between North and South-facing offices is due to the amount of the solar heat gain.

		North					South				
	U	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}
W	1.2	-42	-52	-43	41	12	7	-52	-43	41	61
	2.6	-102	-113	-43	41	12	-53	-113	-43	41	61
M	1.2	10	-32	-26	41	27	51	-32	-26	41	68
	2.6	-27	-69	-26	41	27	14	-69	-26	41	68
S	1.2	59	-9	-7	41	34	88	-9	-7	41	63
	2.6	48	-19	-7	41	34	78	-19	-7	41	63

Table 6.3 Effect of U-value on energy demand of North and South-facing offices in Caribou using steady-state calculation, assuming $g = 0.5$, SC1

Table 6.4 shows the results for North and South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.3$ and the U-value is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. It can be seen that there is generally a higher heating demand in winter and mid-season but lower cooling demand in mid-season and summer, in offices facing in both orientations. Lowering the U-value can reduce the annual energy demand by 88kWh/m^2 in a North-facing office and 86kWh/m^2 in a South-facing office. Therefore, reducing the U-value is more effective when $g = 0.3$ than when $g = 0.5$.

		North					South				
	U	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}
W	1.2	-51	-52	-43	41	3	-38	-52	-43	41	16
	2.6	-112	-113	-43	41	3	-99	-113	-43	41	16
M	1.2	-10	-32	-26	41	7	1	-32	-26	41	17
	2.6	-47	-69	-26	41	7	-36	-69	-26	41	17
S	1.2	33	-9	-7	41	9	41	-9	-7	41	16
	2.6	23	-19	-7	41	9	31	-19	-7	41	16

Table 6.4 Effect of U-value on energy demand of North and South-facing offices in Caribou assuming $g = 0.3$ using steady-state calculation, SC1

The effect of the g-value on the seasonal and annual energy demand can be seen when comparing Table 6.3 and Table 6.4. When g-value is reduced from 0.5 to 0.3, Q_{sol} is generally reduced. In winter, lowering the g-value increases the heating demand. For example, in a North-facing office when U is $1.2\text{W/m}^2\text{K}$, the heating demand is -42kWh/m^2 when $g = 0.5$, but -51kWh/m^2 when the g-value is decreased to 0.3.

Lowering the g-value can reduce cooling load in summer and some cases in mid-season, due to the associated reduction in the solar heat gain. The net effect is that, annually, when $U = 1.2\text{W/m}^2\text{K}$, reducing the g-value from 0.5 to 0.3 reduces the annual energy demand from 111kWh/m^2 to 94kWh/m^2 and 146kWh/m^2 to 80kWh/m^2 , in North and South-facing offices respectively. However, when $U = 2.6\text{W/m}^2\text{K}$, reducing the g-value from 0.5 to 0.3 increases the annual energy demand from 177kWh/m^2 to

182kWh/m² and 145kWh/m² to 166kWh/m², in North and South-facing offices respectively. Hence, reducing the g-value is only effective when the U-value is low.

6.1.2 Annual results, Tas

Climate data

Table 6.5 shows the seasonal averaged values of hourly weather data used in the Tas simulations. It can be seen that winter is the coldest time of the year with the least amount of solar irradiance, whereas summer is the hottest time of the year with the highest amount of solar irradiance. The indoor design temperature has been set as 21°C.

Caribou	T _{max} (°C)	T _{min} (°C)	T _{av} (°C)	Solar radiation Wh/m ²
Winter	5.9	-19.3	-7.7	3,285
Mid-season	17.5	-8.0	3.9	5,804
Summer	27.5	5.9	15.5	6,781

Table 6.5 Seasonal average temperature and solar radiation data for Caribou, Tas

Annual results

Figure 6.5 (i, ii, iii, iv) show respectively for North, South, East and West-facing offices in Caribou the effect of U and three levels of g-values on annual energy demand obtained by means of Tas. The annual energy demand ranges between 92kWh/m², i.e. North-facing office when U = 1.2 and g = 0.3, and 145kWh/m², i.e. West-facing office when U = 2.6W/m²K and g = 0.5. It can be seen that utilising facades with low U-values can reduce the annual energy demand in all test offices except South-facing offices using facades with a g-value of 0.5.

The energy reduction effect of lowering the U-value is more obvious with lower g-value facades. For example, in a South-facing test office, lowering the U-value of the facade when g = 0.3 can reduce the office's annual energy demand by around 25kWh/m², whereas it has little effect when the g-value is 0.5. Moreover, the effect of lowering the U-value is most obvious in North-facing test offices. The results also show that reducing the g-value of the facades is beneficial irrespective of office orientation; particularly at lower U-values, and especially in South-facing offices.

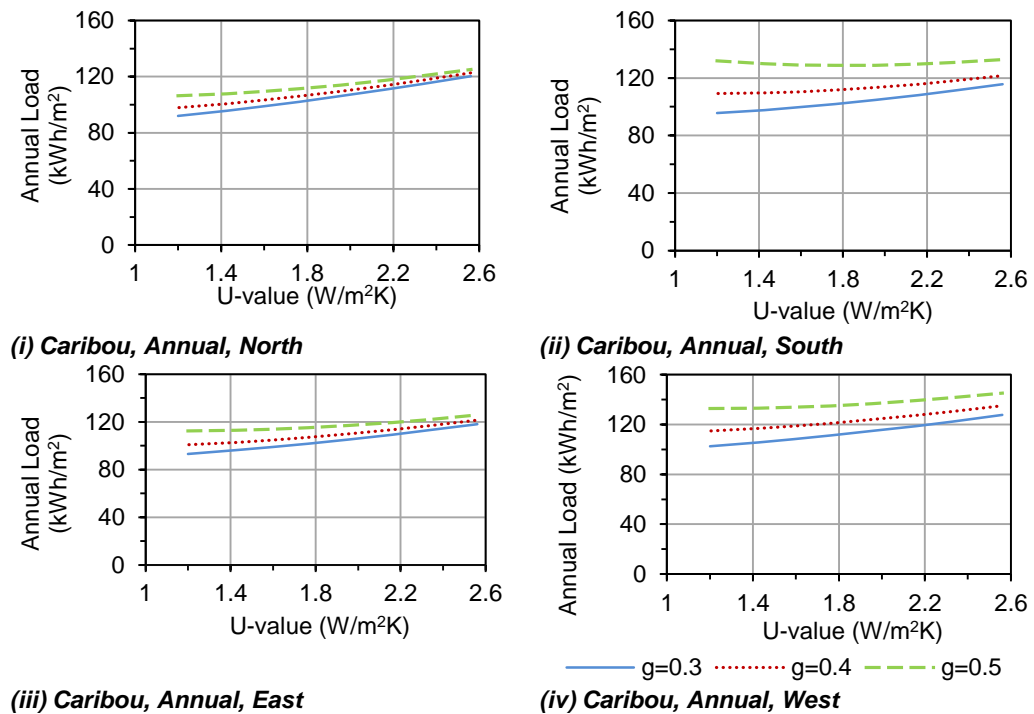


Figure 6.5 Effect of U and g-values and building orientation on annual heating/cooling load of test office, Tas, Caribou, SC1

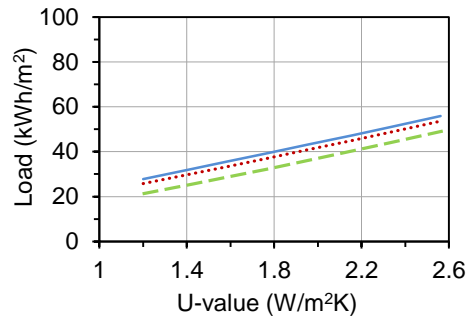
6.1.3 Seasonal performance of Caribou, Tas

In order to understand these trends, the energy demand by season was determined. Figure 6.6 to Figure 6.8 show respectively the total energy required for offices in winter, mid-season and summer, obtained via Tas. It can be seen that the effect on energy demand of lowering the U-value and g-value of the facade varies by season.

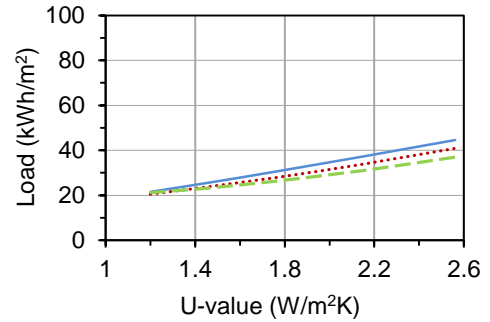
Figure 6.6 shows that in winter, around 50% reduction in energy demand can be achieved when the U-value of the facade is reduced from 2.6 W/m²K to 1.2 W/m²K, irrespective of office orientation.

In mid-season, lowering the U-value has little effect on the annual energy demand when $g = 0.3$, but the energy demand increases when g is 0.4 and above, particular in offices facing South.

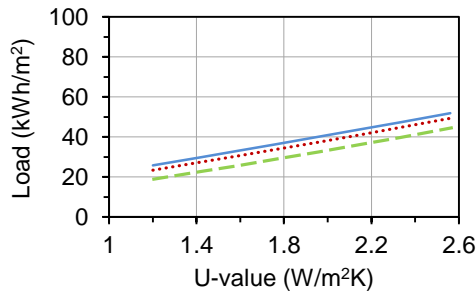
In summer, the energy demand increases with decreasing U-value, irrespective of office orientations. Lowering the g-value is most beneficial in summer, as well as South and West-facing offices in mid-season, but it increases energy demand in winter, irrespective of office orientation.



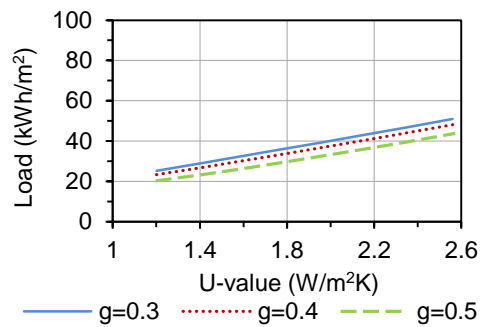
(i) Caribou, Winter, North



(ii) Caribou, Winter, South

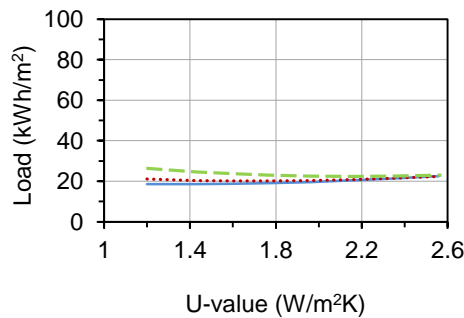


(iii) Caribou, Winter, East

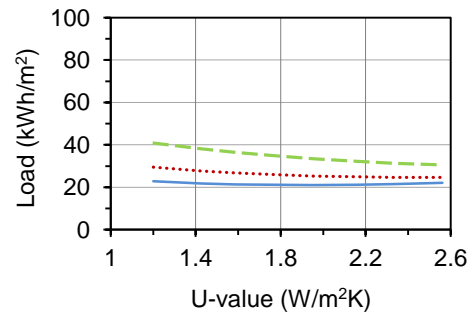


(iv) Caribou, Winter, West

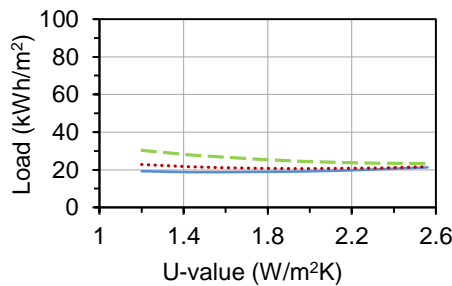
Figure 6.6 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Caribou, SC1



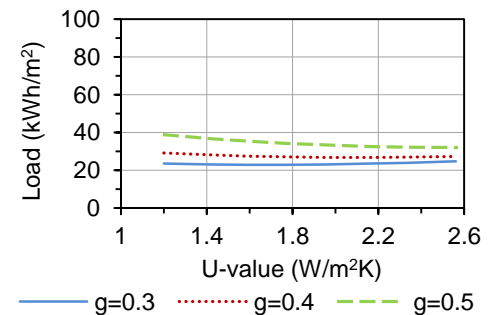
(i) Caribou, Mid-season, North



(ii) Caribou, Mid-season, South



(iii) Caribou, Mid-season, East



(iv) Caribou, Mid-season, West

Figure 6.7 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Caribou, SC1

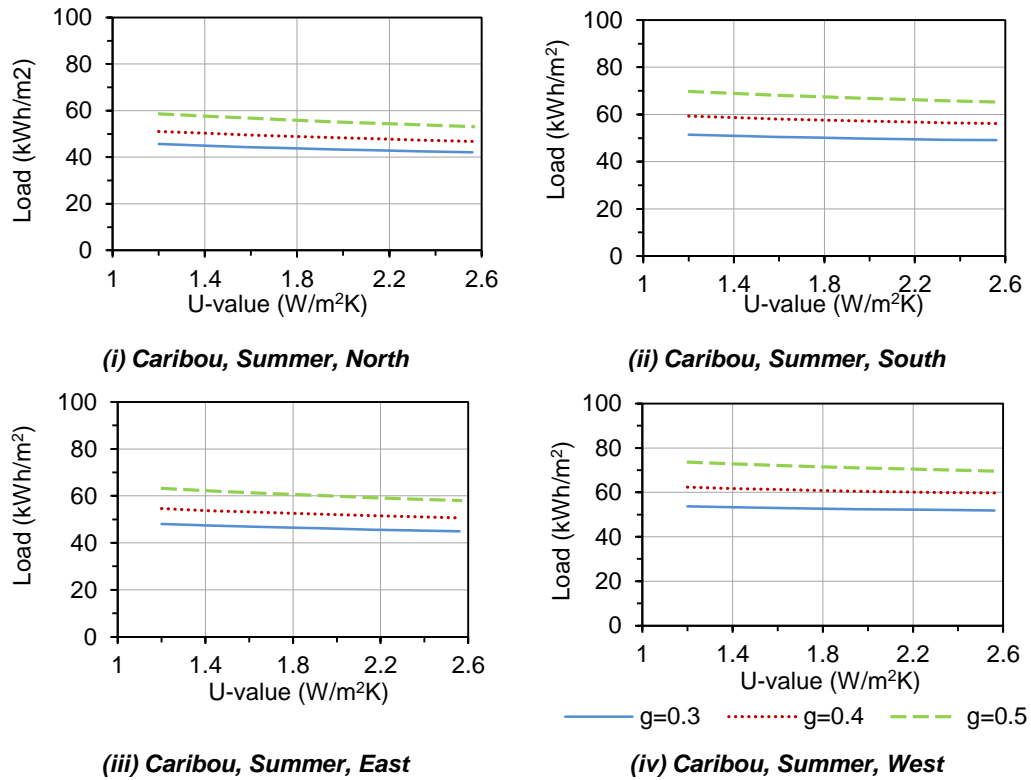


Figure 6.8 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in summer, Caribou, SC1

An examination of the nature of seasonal energy usage reveals that the test offices require heating mostly in winter, a mix of heating and cooling in mid-season and cooling only in summer. Figure 6.9 and Figure 6.10 show the heating and cooling demand of tested offices facing North, South, East and West in winter and mid-season.

In winter, Figure 6.9 shows that heating is the dominant load, irrespective of office orientation. South-facing offices require a small amount of cooling, which increases with decreasing U-value. In contrast, the heating requirement decreases with decreasing U-value. In mid-season (Figure 6.10), there is a mix of heating and cooling load. When the U-value decreases, the heating demand decreases but the cooling demand increases. When $g = 0.4$ and $g = 0.5$, and in particular in South and West-facing offices, the cooling requirement is higher than the heating requirement. Therefore, reducing the U-value increases the dominant cooling demand and hence the total load. When $g = 0.3$, varying the U-value changes the proportion of the heating and cooling required, but it does not have much effect on the total energy demand, which is the sum of the heating and cooling loads. In all seasons, lowering the g-value increases the heating demand but reduces the cooling demand.

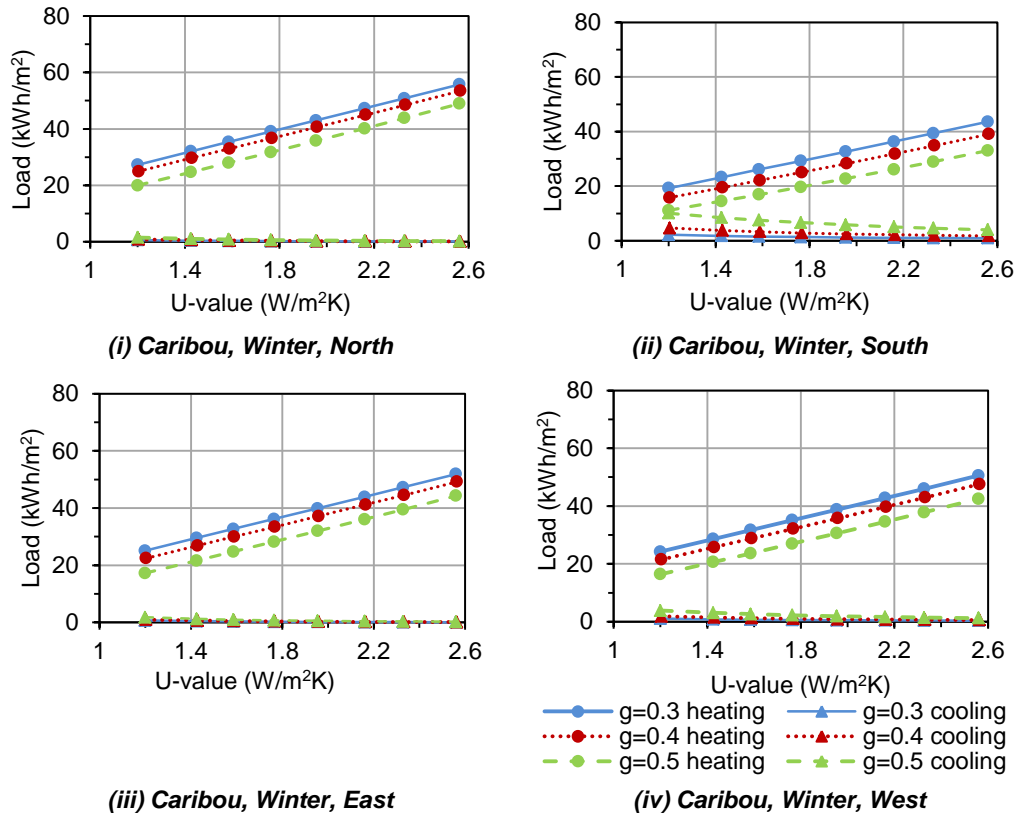


Figure 6.9 Effect of U and g values and building orientation on heating/cooling load of test office using Tas in winter, Caribou, SC1

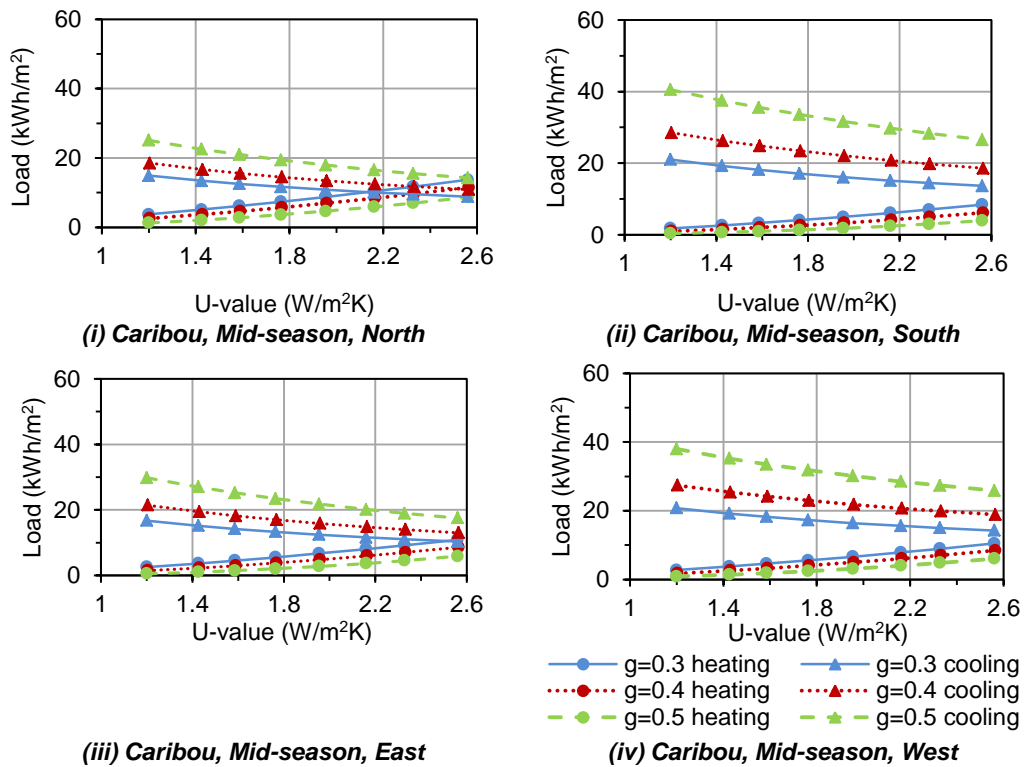


Figure 6.10 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Caribou, SC1

Breakdown of the results

Further insights are obtained by considering values of the principal factors influencing energy demand, namely:

- Conduction heat gain/loss through facade (Q_{cond} , kWh/m²)
- Ventilation heat gain/loss (Q_{air} , kWh/m²)
- Internal heat gain (Q_{int} , kWh/m²)
- Solar heat gain (Q_{sol} , kWh/m²)
- Heat gain/loss from adjacent spaces due to building heat transfer (Q_b , kWh/m²)

Table 6.6 shows the results for South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and U is either 1.2W/m²K or 2.6W/m²K. The values for each individual component in the table are the summations of hourly data for each season. Note that Q_h and Q_c represent, respectively, the heating and cooling load in kWh/m². Q_b measures the heat gain/loss through internal building elements, e.g. walls, floors, ceilings and heat temporarily stored in the air (EDSL 2015). Q_b is not discussed here, as the difference it makes is small compared with the other components of the heat balance. Additionally, it does not affect the overall results; this applies to all following cases in this chapter.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	13	8	-45	-38	40	46	-8
	2.6	35	3	-78	-38	40	46	-2
M	1.2	1	37	-32	-21	41	55	-7
	2.6	4	25	-52	-21	41	55	-4
S	1.2	0	67	-15	-3	41	49	-5
	2.6	0	64	-21	-3	41	49	-3

Table 6.6 Effect of U-value on heating/cooling load when $g = 0.5$ for South-facing offices, SC1

In winter, the coldest time of the year with $\Delta T = 29.6^\circ\text{C}$, it can be seen that the heating load is at its highest because of the significant amount of heat losses due to conduction and ventilation. Lowering the facade's U-value from 2.6W/m²K to 1.2 W/m²K reduces the heat loss due to conduction from -78 to -45 kWh/m², and hence the heating requirement (Q_h) from 35kWh/m² to 13kWh/m². Although there is a rise in the cooling load (Q_c) from 3kWh/m² to 8kWh/m², the total load reduces from 38kWh/m² to 21kWh/m².

In mid-season, because the ΔT is smaller, there is a decrease in heat losses from conduction and ventilation. The combination of Q_{sol} , which increases from 46kWh/m² to

55kWh/m², and Q_{int} , give rise to net cooling requirements. Lowering the U-value reduces the heat loss due to conduction, which leads to an increase in the cooling demand, as well as the total load which increases from 29 kWh/m² to 38 kWh/m². In summer, the outdoor average temperature is 16.8°C, and therefore Q_{air} , falls further to -4kWh/m² and the heat loss due to conduction is also reduced. Q_{int} and Q_{sol} are still high, and hence there is a cooling requirement in the test offices. A lower U-value facade reduces the conduction heat losses, which is not beneficial in summer conditions.

Overall, using a lower U-value facade with a g-value of 0.5 in offices facing South does not have much impact. The reduction in heating demand in winter is around the same as the increase in cooling load in mid-season and summer.

However, in the rest of the cases, reducing the U-value of the facade is beneficial. For example, Table 6.7 shows the values of the principal factors for a North-facing office in winter (W), mid-season (M) and summer (S), assuming $g = 0.3$ and U is either 1.2 W/m²K or 2.6W/m²K.

Compared with South-facing offices using a facade with a g-value of 0.5, a North-facing office with $g = 0.3$ has a higher heating demand in winter and a lower cooling demand in mid-season and summer, due to the smaller Q_{sol} . Reducing the U-value from 2.6 to 1.2W/m²K can almost halve the heating demand in winter and cause a small rise in the cooling demand. In mid-season and summer, lowering the U-value limits the heat loss due to conduction, and hence increases the cooling requirement as well as the total loads by 3kWh/m² and 5kWh/m², respectively. Overall, lowering the U-value saves more energy in winter than the energy increase it causes in mid-season and summer. Therefore, annually, it reduces the energy demand by 20kWh/m².

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	1.2	23	1	-43	-38	40	11	8
	2.6	51	0	-79	-38	40	11	15
Mid-season	1.2	2	23	-31	-21	41	25	6
	2.6	10	13	-52	-21	41	25	10
Summer	1.2	0	57	-14	-3	41	30	2
	2.6	0	52	-22	-3	41	30	5

Table 6.7 Effect of U-value on heating/cooling load when $g = 0.3$ for North-facing offices using Tas, SC1

Effect of g-value

Lowering the g-value reduces the annual energy demand in all offices, especially when the U-value is lower. For instance, Table 6.8 shows for a South-facing office the effect of the g-value on seasonal energy demand, assuming that the U-value is $1.2 \text{ W/m}^2\text{K}$. Table 6.9 shows the same results for a North-facing office. In winter, it can be seen that lowering the g-value increases the heating requirement but reduces in the cooling load. The net effect is zero in the case of a South-facing office (Table 6.8). However, in a North-facing office, where there is less solar heat gain and therefore higher heating demand, it increases the total load. In both North and South-facing offices, lowering the g-value reduces the solar heat gain and hence the cooling requirement, and in turn the total load in mid-season and summer. Overall, lowering the g-value can reduce the annual energy demand by 31kWh/m^2 and 13kWh/m^2 , in South and North facing offices respectively.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	19	2	-41	-38	40	24	-3
	0.4	16	5	-43	-38	40	35	-6
	0.5	13	8	-45	-38	40	46	-8
M	0.3	2	21	-27	-21	41	28	-3
	0.4	1	28	-29	-21	41	42	-5
	0.5	1	37	-32	-21	41	55	-7
S	0.3	0	51	-10	-3	41	25	-2
	0.4	0	59	-13	-3	41	37	-3
	0.5	0	67	-15	-3	41	49	-5

Table 6.8 Effect of g-value on energy demand of South-facing offices in Caribou, assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC1

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	27	1	-42	-38	40	6	7
	0.4	25	1	-43	-38	40	8	7
	0.5	23	1	-43	-38	40	11	8
M	0.3	4	15	-27	-21	41	13	5
	0.4	3	18	-29	-21	41	19	5
	0.5	2	23	-31	-21	41	25	6
S	0.3	0	46	-11	-3	41	16	2
	0.4	0	51	-12	-3	41	23	2
	0.5	0	57	-14	-3	41	30	2

Table 6.9 Effect of g-value on energy demand of North-facing offices in Caribou using Tas, assuming $U = 1.2 \text{ W/m}^2\text{K}$, SC1

6.2 Effect of prolonged office working hours, SC2

This section presents the test results for Caribou under a prolonged working hour scenario (SC2). The scenario considers 16 working hours per day, 7 days a week, with assumed internal gains of 33.7W/m^2 in tested offices under Caribou's current climate conditions.

6.2.1 Steady-state study

Figure 6.11 shows the effect of U and g-values on annual energy demand in offices facing North, South, East and West in Caribou under SC2, obtained by the steady-state method. It can be seen that lowering the U-value reduces annual load in all offices apart from the case $g = 0.5$ and $U = 1.2\text{ W/m}^2\text{K}$ in South orientation. Lowering the g-value is more beneficial when the U-value is lower and in South, East and West-facing offices. These annual trends are similar to those in SC1.

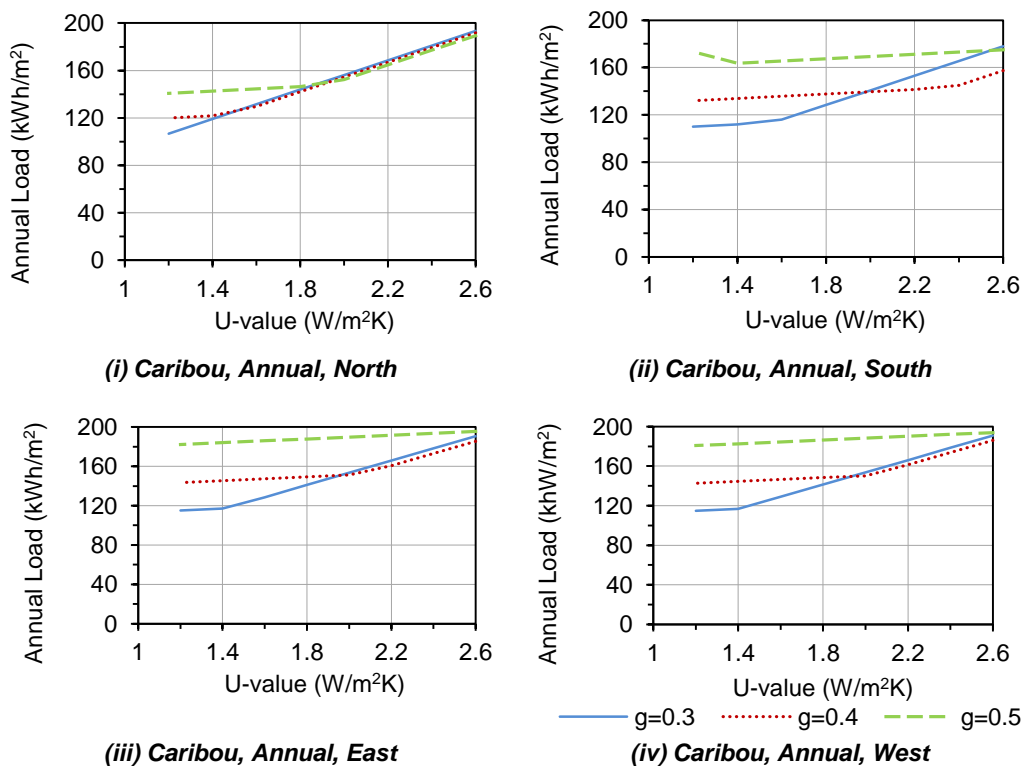


Figure 6.11 Effect of U and g-values and building orientation on annual heating/cooling load of test office using steady state calculation, Caribou, SC2

Seasonal results

Figure 6.12 to Figure 6.14 show the office seasonal energy demand in winter, mid-season and summer respectively. The seasonal trends in SC2 are similar to those in SC1. Reducing the U-value reduces the total energy demand, which is all due to heating, by overall 50% in winter; it increases the cooling need during mid-seasons and summer. Lowering the g-value is only beneficial when there is a net cooling demand, for example in summer and some cases in mid-season. Furthermore, extending the workings hours generally makes little difference to the amount of heating needed in winter, but increases the cooling demand in mid-season and summer.

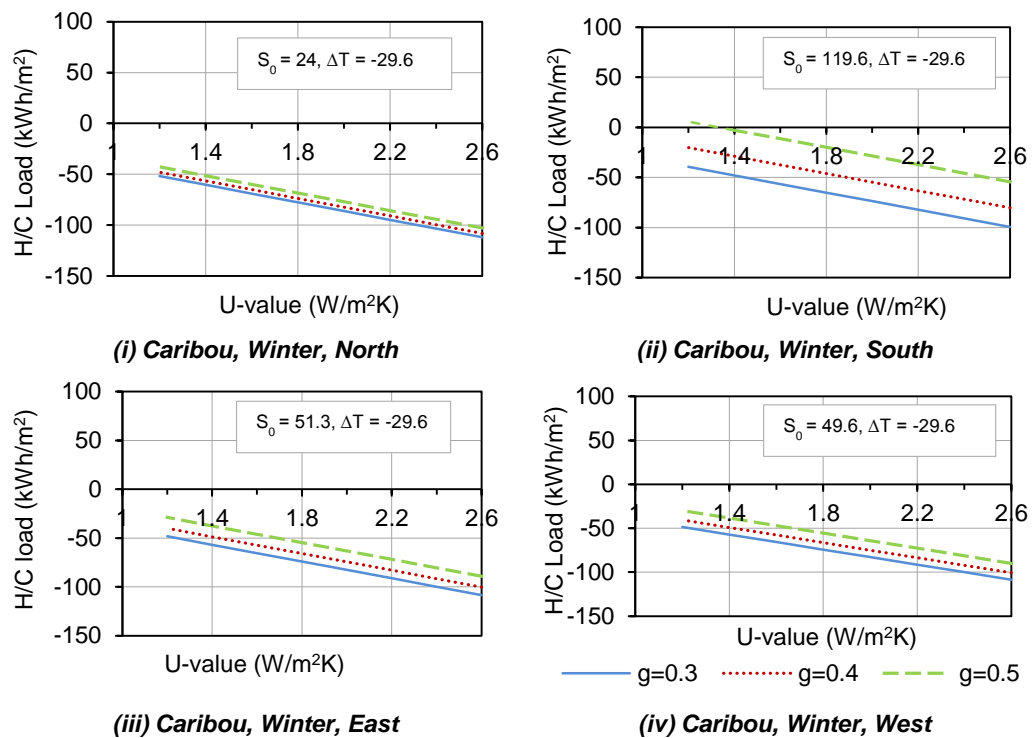


Figure 6.12 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in winter, Caribou, SC2

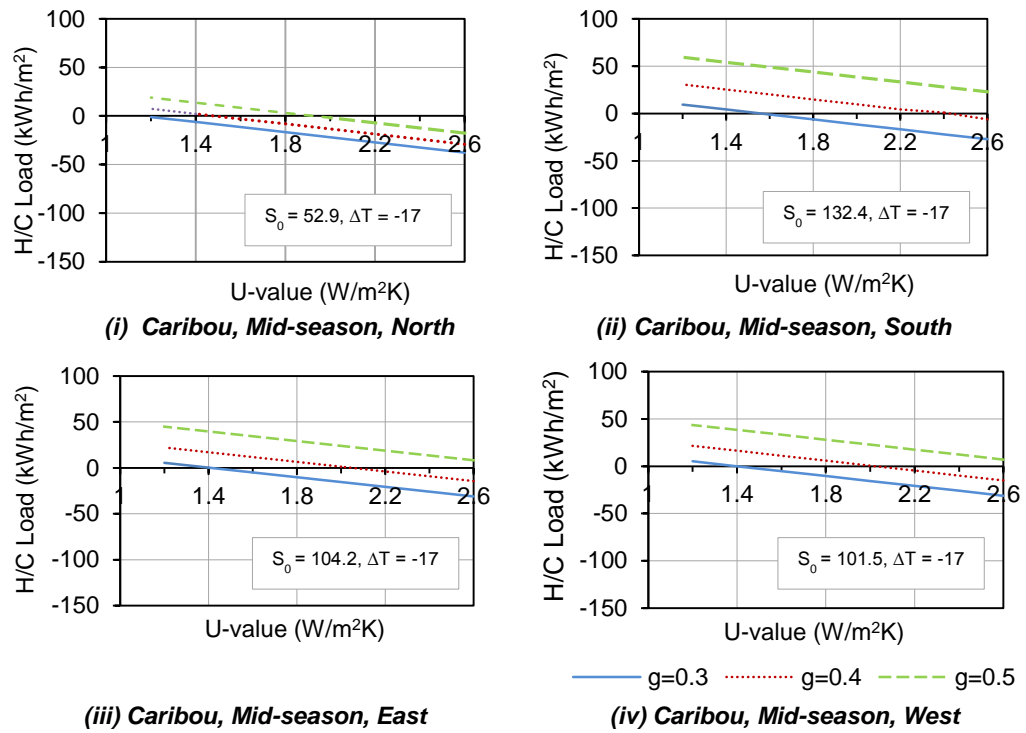


Figure 6.13 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in mid-season, Caribou, SC2

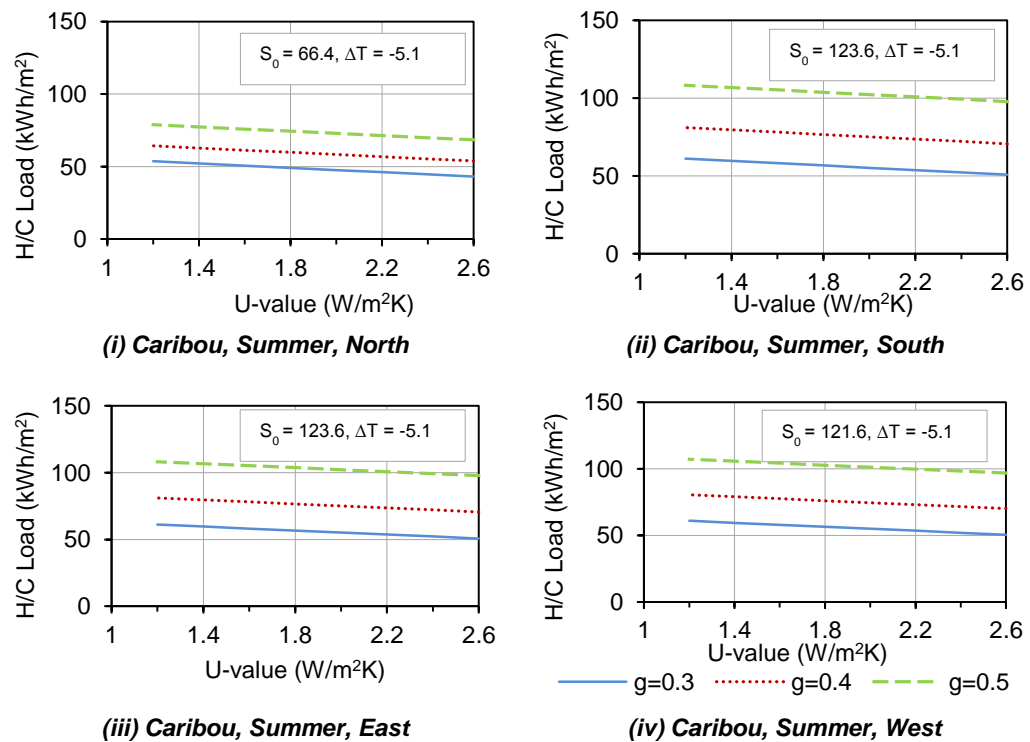


Figure 6.14 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in summer, Caribou, SC2

Breakdown of the results

Table 6.10 shows the effect of lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ on seasonal energy demand for North and South-facing offices, assuming a g-value of 0.5. whereas the g is assumed to be 0.3 in Table 6.11. It can be seen that prolonging working hours from 10 to 16 hours raises internal heat gains from 41kWh/m^2 to 66kWh/m^2 . This is also the case in SC1: the facade with U-value of $1.2\text{W/m}^2\text{K}$ performs better when there is a heating requirement as it reduces the heat loss due to conduction, for example in winter. When there is a net cooling requirement, it increases the cooling load because it unfavourably reduces the Q_{cond} .

Compared with SC1, it can be seen that in winter in SC2, the effect of the rise in internal gains is offset by the increased ventilation loss due to the longer operating hours, hence there is not much change in heating requirements. The effect of prolonged working hours, i.e. increasing the cooling demand, is most obvious in the summer, when the rise in ventilation heat loss is small due to the smaller temperature difference between indoors and outdoors.

		North					South				
	U	Q	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}
W	1.2	-43	-52	-69	66	12	6	-52	-69	66	61
	2.6	-104	-113	-69	66	12	-55	-113	-69	66	61
M	1.2	19	-32	-42	66	27	60	-32	-42	66	68
	2.6	-18	-69	-42	66	27	23	-69	-42	66	68
S	1.2	79	-9	-12	66	34	108	-9	-12	66	63
	2.6	68	-19	-12	66	34	98	-19	-12	66	63

Table 6.10 Effect of U-value on seasonal energy demand of North and South-facing offices using steady-state calculation, Caribou, assuming g = 0.5, SC2

		North					South				
	U	Q	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}
W	1.2	-52	-52	-69	66	3	-40	-52	-69	66	16
	2.6	-113	-113	-69	66	3	-100	-113	-69	66	16
M	1.2	-1	-32	-42	66	7	9	-32	-42	66	17
	2.6	-38	-69	-42	66	7	-27	-69	-42	66	17
S	1.2	54	-9	-12	66	9	61	-9	-12	66	16
	2.6	43	-19	-12	66	9	51	-19	-12	66	16

Table 6.11 Effect of U-value on seasonal energy demand of North and South-facing offices using steady-state calculation, Caribou, assuming g = 0.3, SC2

6.2.2 Annual results for Caribou, Tas

Figure 6.15 (i, ii, iii, iv) shows the effect of lowering the U-value and g-value of the facades on the annual load of test offices facing North, South, East and West under the SC2 condition. Generally, due to the longer working hours, the annual energy demand found in the test offices in SC2 is higher than in SC1, ranging between 136 and 193 kWh/m². It can be seen that lowering the U-value of the facade can reduce the annual energy demand in all offices, irrespective of building orientation and g-values. Similar to the SC1 annual results, lowering the U-value has the larger effect when the g-value is lower at 0.3, and especially in North-facing offices. The load reduction as a result of lowering the U-value in SC2 is between 11 kWh/m² and 34 kWh/m², and it is larger than that in SC1. The results also show that reducing the g-value of the facades is also beneficial in all test offices, especially when the U-value is lower or in South-facing offices.

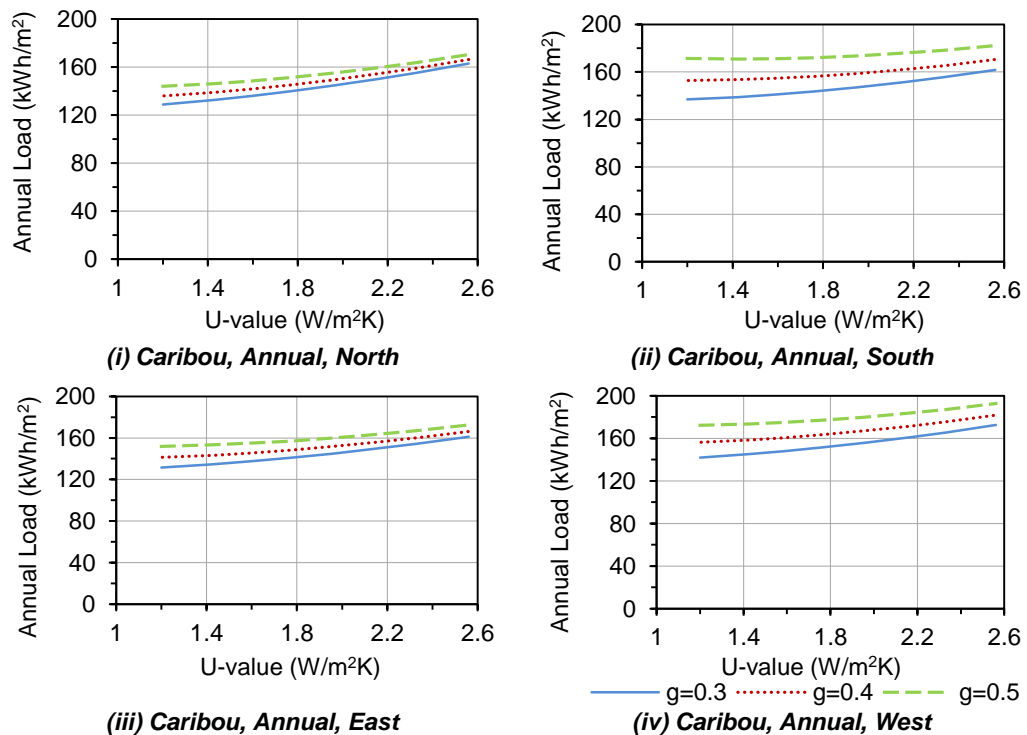


Figure 6.15 Effect of U and g-values and building orientation on annual heating/cooling load of test office Tas, Caribou, SC2

6.2.3 Seasonal performance of Caribou, Tas

Again, the energy demand by season was determined. Figure 6.16 to Figure 6.18 show respectively the total energy required for offices in winter, mid-season and summer, obtained via Tas. Figure 6.16 shows that in winter, irrespective of office orientation, around 50% of the energy demand reduction can be achieved when the U-value of the facade is reduced from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$. In mid-season (Figure 6.17) and summer (Figure 6.18), lowering the U-value increases the annual energy demand except when g is 0.3 during mid-season. In mid-season, the trend lines are curved, unlike in summer and winter. Lowering the g-value is most beneficial in summer, and in South and West-facing offices in mid-season, whereas it increases the energy demand in winter by a small amount, irrespective of office orientation.

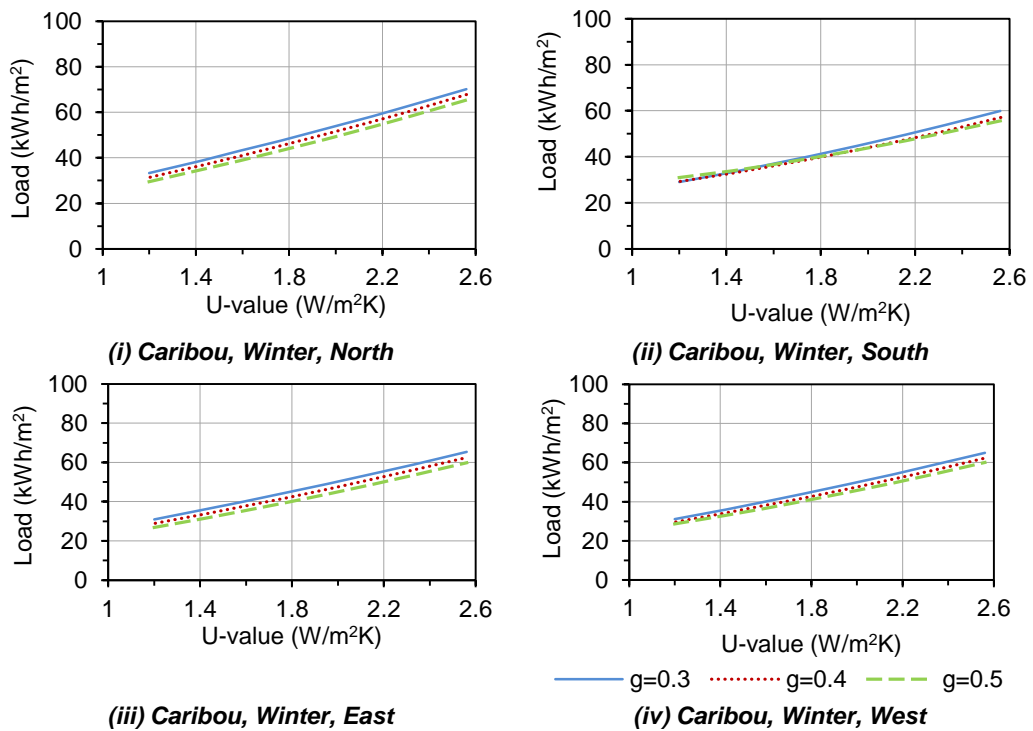


Figure 6.16 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Caribou, SC2

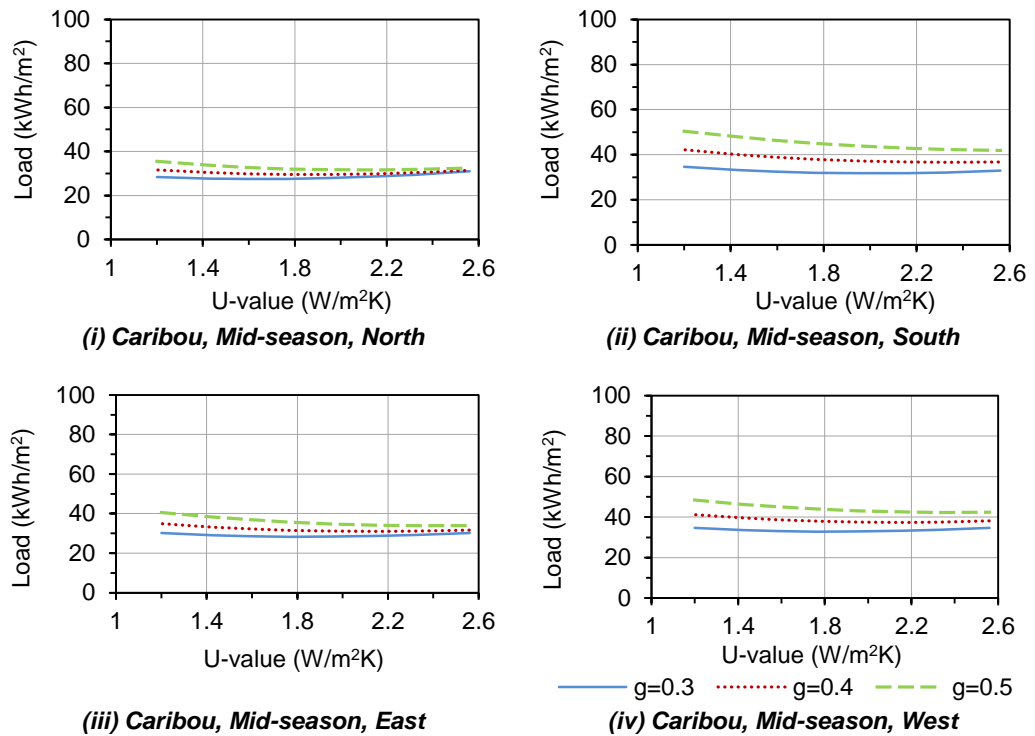


Figure 6.17 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Caribou, SC2

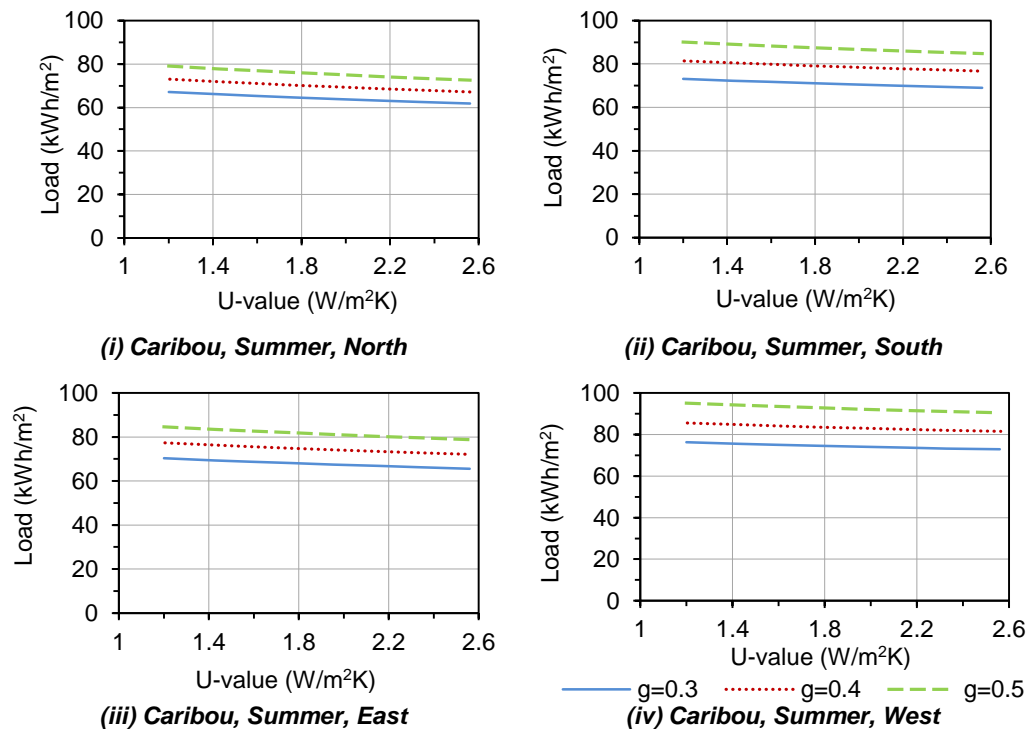


Figure 6.18 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in summer, Caribou, SC2

Figure 6.19 and Figure 6.20 show the nature of the energy demand in winter and mid-season. It can be seen that heating is the main load and there is a small amount of cooling load in winter, especially in offices facing South with a higher g-value facade. In mid-season (Figure 6.20), there is higher requirement for cooling than heating. Again, a South-facing office with a g-value of 0.5 has the highest cooling load. In summer, there is only a cooling requirement and no heating load.

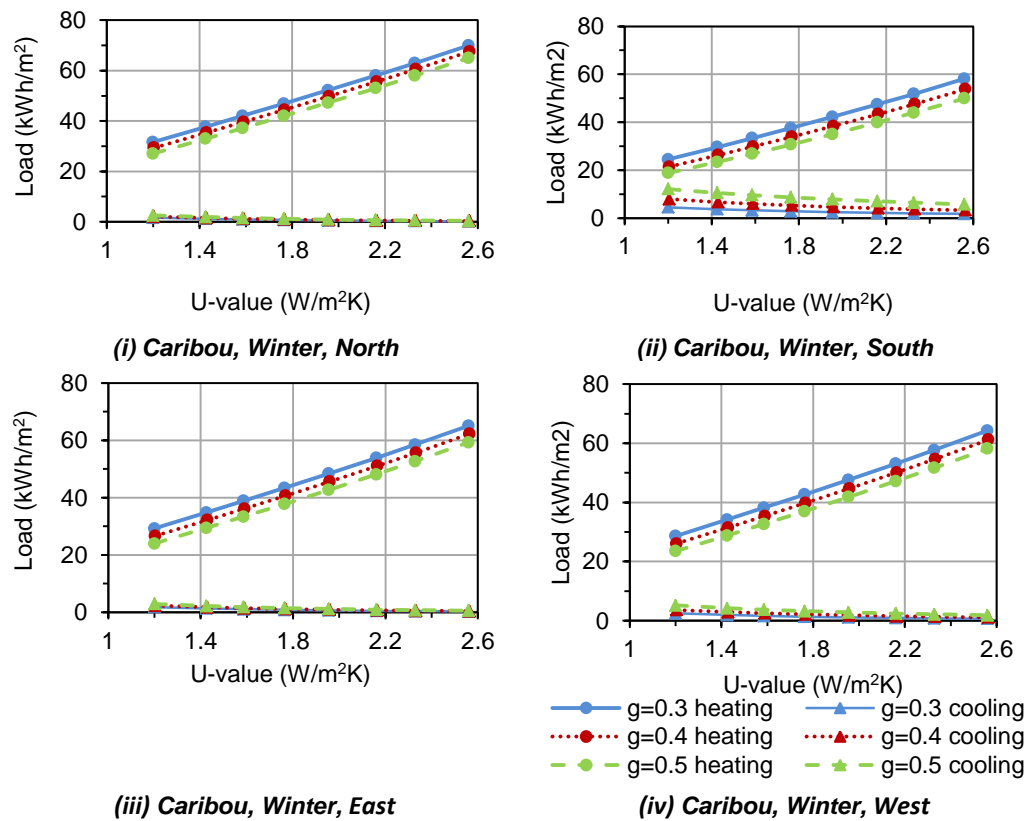


Figure 6.19 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Caribou, SC2

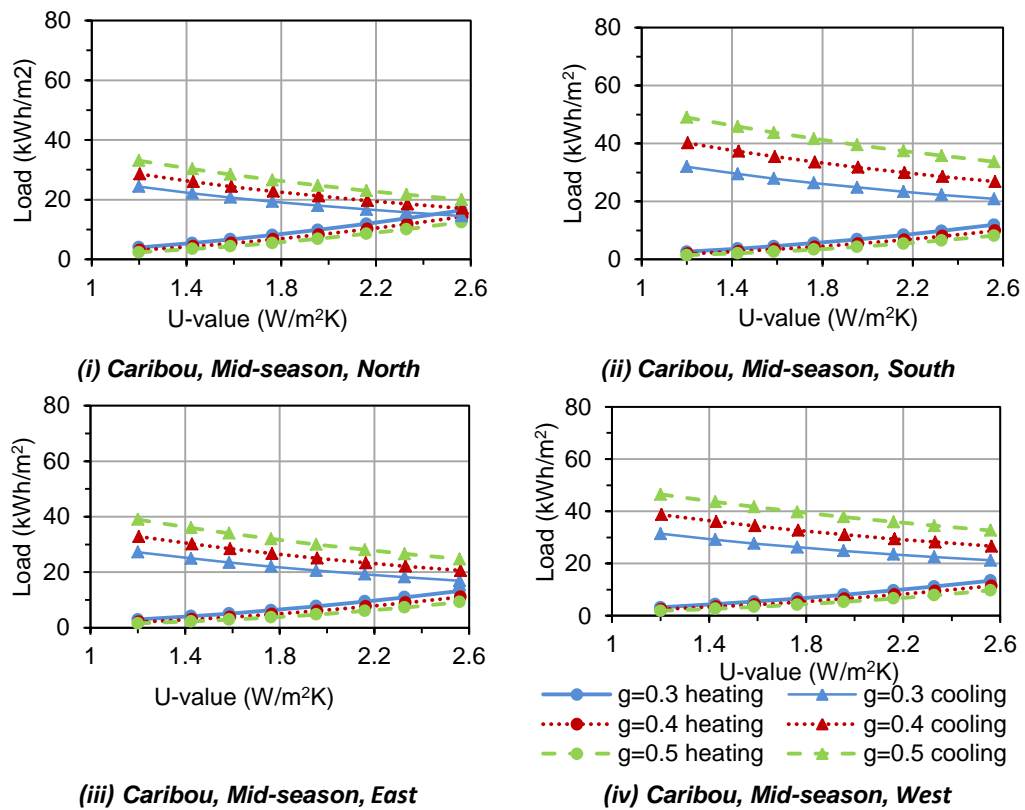


Figure 6.20 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Caribou, SC2

Breakdown of the results

Table 6.12 shows the results for South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and the U-value is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. In SC2, the general trends remain the same: lowering the U-value is beneficial in winter because it can reduce the dominant heating load, and it increases the total load in mid-season and summer because it increases the dominant cooling demand by limiting the conduction heat losses. Because working hours are extended from 10 to 16 hours, there is more heat loss due to conduction and ventilation, and an increase in the internal heat gain. In winter, the net effect is that both heating and cooling loads increase by a small amount. During mid-season and summer, the rise in internal heat gain is partially offset by the increase in the heat loss due to ventilation and conduction; but there is still a rise in the cooling demand.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	19	12	-48	-62	65	46	-6
	2.6	50	6	-91	-62	65	46	-1
M	1.2	1	49	-33	-36	66	55	-5
	2.6	8	34	-58	-36	66	55	-2
S	1.2	0	90	-14	-8	66	49	-2
	2.6	0	85	-21	-8	66	49	-1

Table 6.12 Effect of U-value on energy demand of South-facing offices in Caribou assuming $g = 0.5$, SC2

Effect of g-value

Table 6.13 shows the effect of the g-value on seasonal energy demand for South-facing offices with a facade U-value of $1.2 \text{ W/m}^2\text{K}$. In winter, lowering the g-value from 0.5 to 0.3 increases the heating requirement and reduces cooling need, irrespective of office orientation, hence the net effect is very small. In mid-season and summer, when there is a high cooling need and almost no heating demand, lowering the g-value reduces the cooling load because it reduces the solar heat gain. Overall, lowering the g-value can reduce the annual energy demand by 34 kWh/m^2 in South-facing offices.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	24	5	-45	-62	65	24	-2
	0.4	21	8	-47	-62	65	35	-4
	0.5	19	12	-48	-62	65	46	-6
M	0.3	3	32	-29	-36	66	28	-1
	0.4	2	40	-31	-36	66	42	-3
	0.5	1	49	-33	-36	66	55	-5
S	0.3	0	73	-10	-8	66	25	0
	0.4	0	81	-12	-8	66	37	-1
	0.5	0	90	-14	-8	66	49	-2

Table 6.13 Effect of g-value on energy demand of South-facing offices in Caribou assuming $U = 1.2 \text{ W/m}^2\text{K}$, SC2

6.3 Effect of lowering internal gain, SC3

This section presents the test results for Caribou under a lower internal gain per floor area scenario, which is 10 working hours per day, 7 days a week, with assumed internal gains of 25W/m^2 in tested offices under Caribou's current climate conditions. Results from Tas simulations are presented here.

6.3.1 Annual results, Tas

Figure 6.21 (i, ii, iii, iv) shows, respectively for North, South, East and West-facing offices in Caribou, the effect of U-values and three levels of g-values on annual energy demand obtained by means of Tas under the SC3 condition. It can be seen that utilising the facades with low U-values can reduce the annual energy demand, irrespective of office orientation. The energy reduction effect of lowering the U-value of the facades is more obvious when the facade's g-value is lower. The results also show that reducing the g-value of the facades is beneficial in South and West-facing offices, especially when the U-value is lower, but the effect is small in North and East-facing offices.

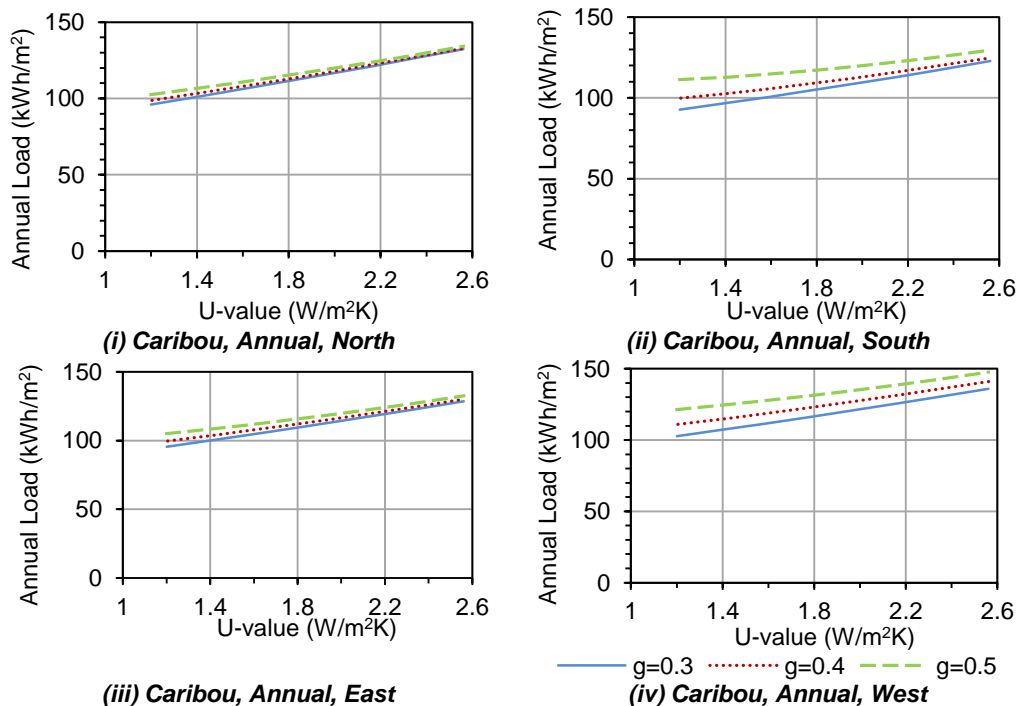


Figure 6.21 Effect of U and g-values and building orientation on annual heating/cooling load of test office under Tas, Caribou, SC3

6.3.2 Seasonal trends, Tas

Again, the energy demand by season was determined. Figure 6.22 to Figure 6.24 show respectively the total energy required for offices in winter, mid-season and summer by obtained via Tas. It can be seen that, compared with SC1, the total load increases in winter, but decreases in mid-season and summer.

Comparing SC1 and SC3 results, changing the U-value and g-value have a different effect on energy demand in mid-season, but the same impact in winter and summer. As in SC1, lowering the U-value can reduce the energy demand by 50% in winter (Figure 6.22), but increases the energy demand by a small amount in summer (Figure 6.24). However, in mid-season (Figure 6.23), instead of increasing the total load, lowering the U-value can reduce the total load in all offices except when $g = 0.5$ in a South-facing office. Lowering the g-value is only beneficial in summer; it increases the total load in winter and has very little effect in mid-season.

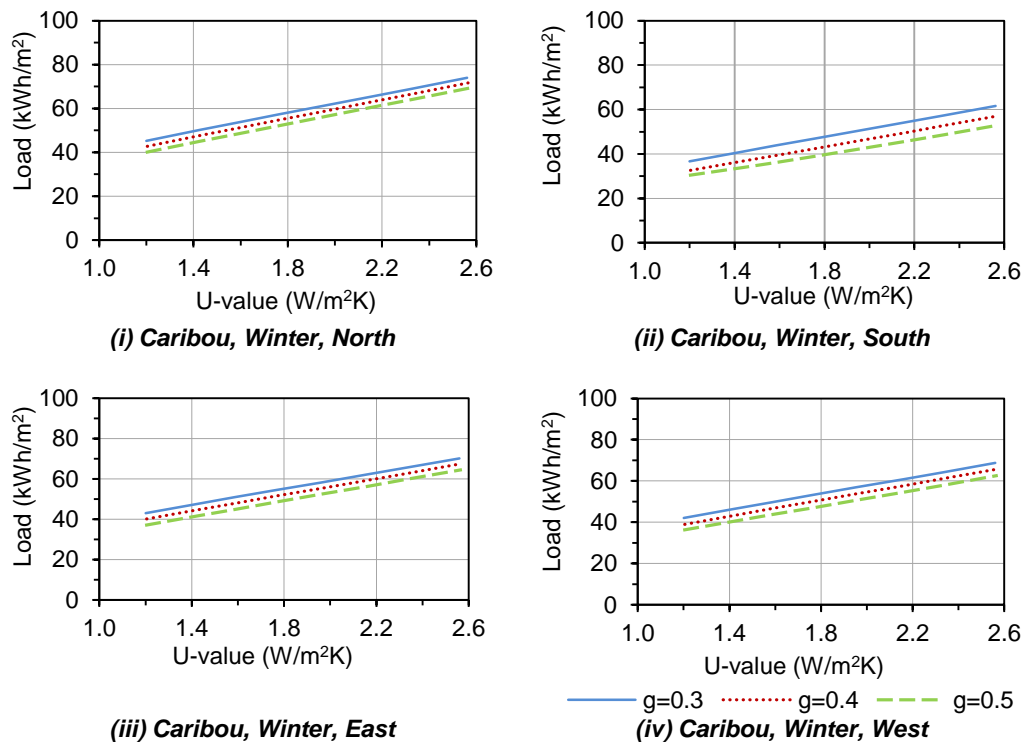


Figure 6.22 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Caribou, SC3

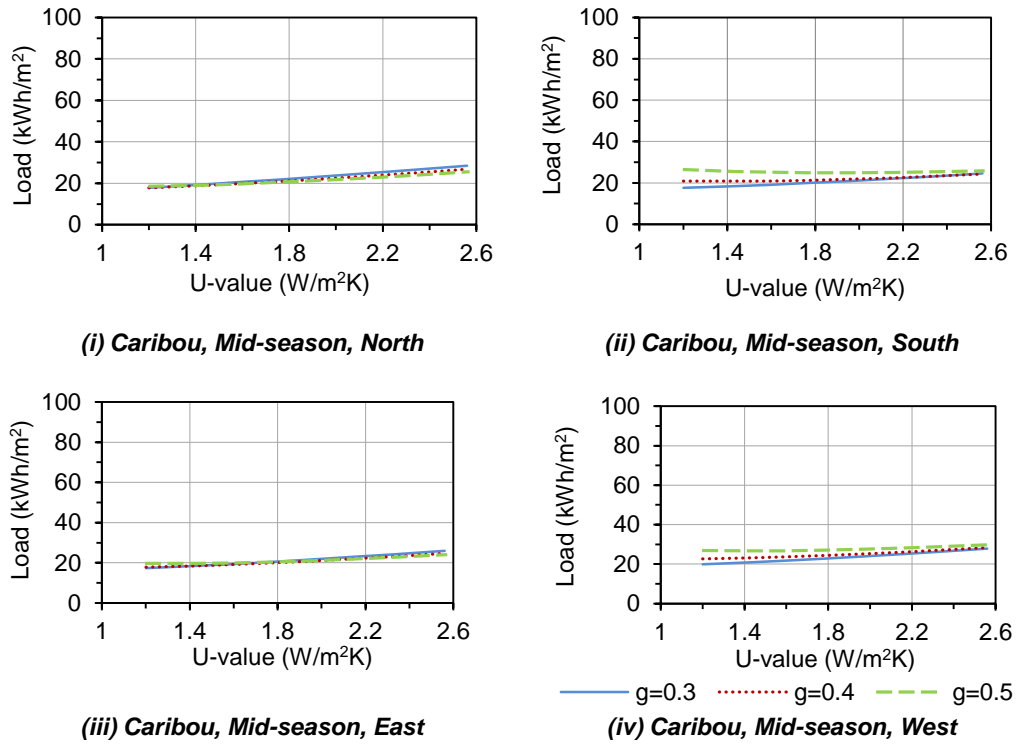


Figure 6.23 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Caribou, SC3

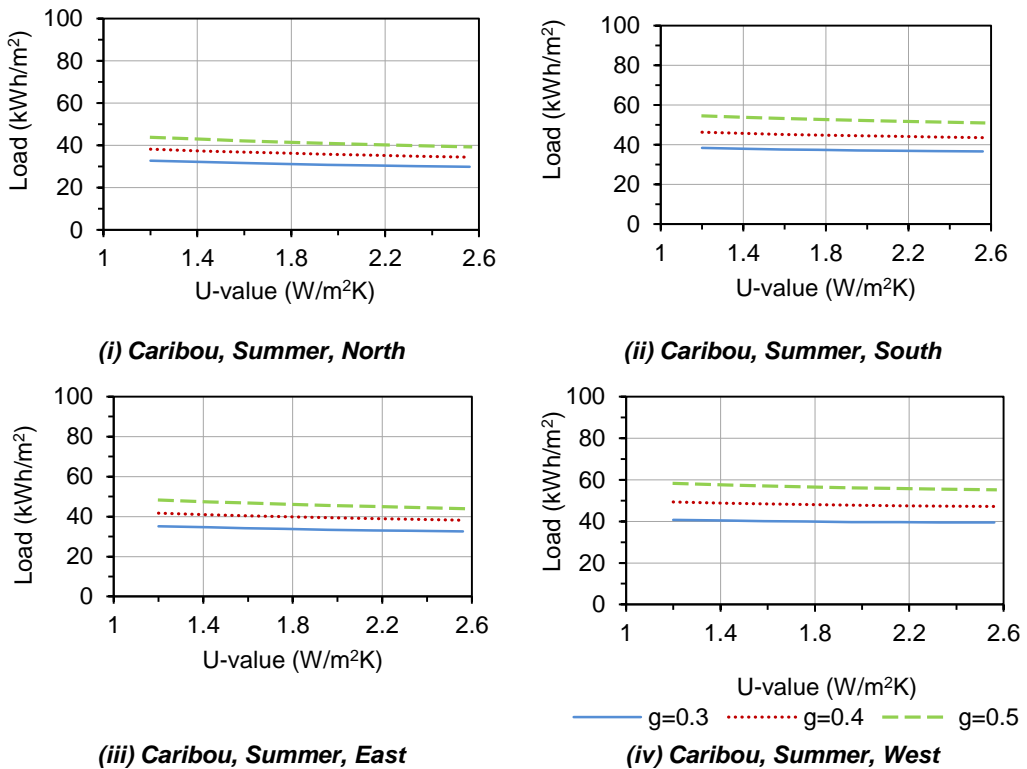


Figure 6.24 Effect of U and g values and building orientation on heating/cooling load of test office using Tas in summer, Caribou, SC3

Figure 6.25 and Figure 6.26 show the heating and cooling demand of tested offices facing North, South, East and West in winter and mid-season. In winter, Figure 6.9 shows that heating is the dominant load in all cases. A small amount of cooling demand in South-facing offices can be seen, and it increases with decreasing U-value. The results show that, when the U-value is decreased, heating demand decreases and cooling load increases, if it exists.

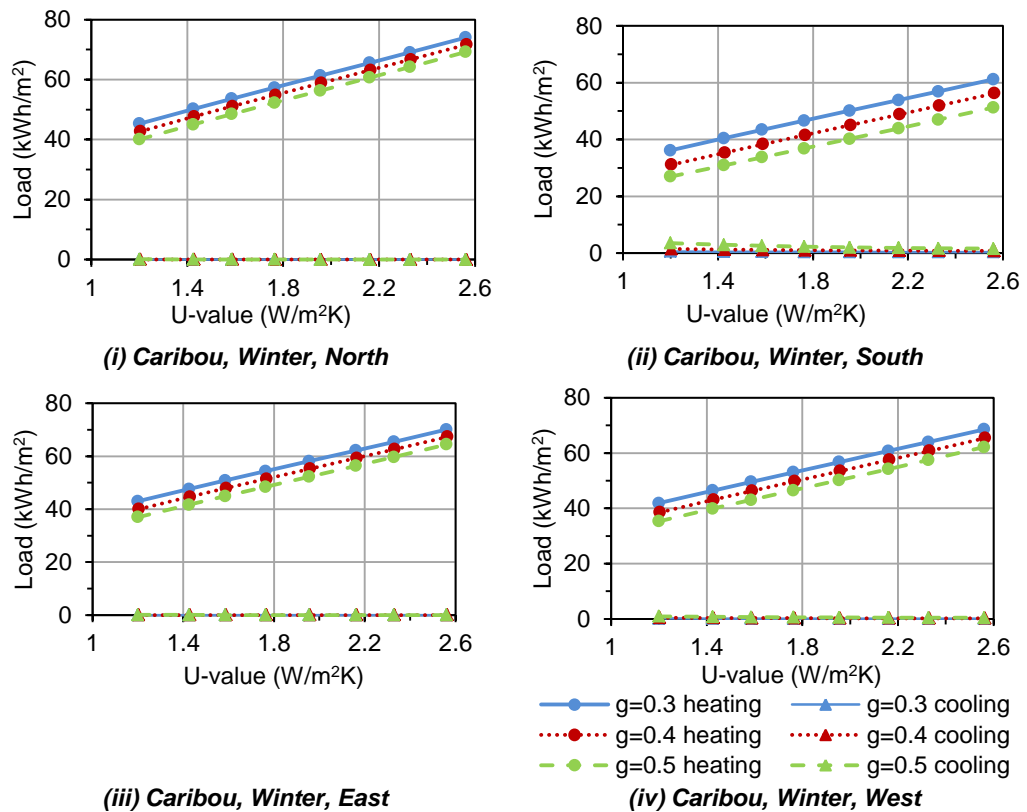


Figure 6.25 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Caribou, SC3

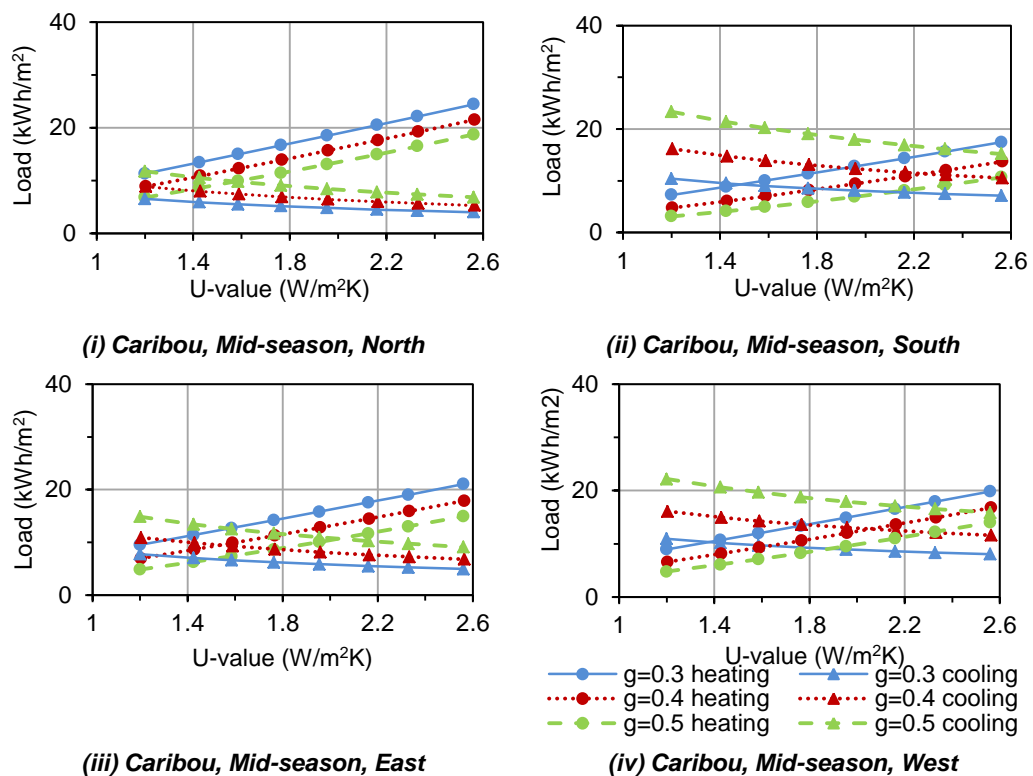


Figure 6.26 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Caribou, SC3

Breakdown of the results

Table 6.14 shows the results for South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and U is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. It can be seen that Q_{in} is reduced from 40kWh/m^2 to 29kWh/m^2 . In winter, the heat losses due to conduction and ventilation are similar to SC1, but because of the reduced amount of internal heat gain, the heating load found in SC3 is higher than in SC1. The decrease in Q_{in} also causes higher heating demand in mid-season, but it reduces the cooling required. Cooling is still dominant in summer.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	27	3	-44	-44	29	46	-9
	2.6	51	2	-77	-44	29	46	-3
M	1.2	3	23	-32	-24	29	55	-9
	2.6	11	15	-51	-24	29	55	-5
S	1.2	0	54	-14	-3	29	49	-6
	2.6	0	51	-20	-3	29	49	-4

Table 6.14 Effect of U-value on energy demand of South-facing offices in Caribou assuming $g = 0.5$ using Tas, SC3

The reasons behind the results are similar. Lowering the U-value of the facade in winter limits the heat loss due to conduction, which is a big proportion in the heat balance due to the large temperature difference between indoors and outdoors, and hence in turn this reduces the total energy demand. In mid-season the average temperature difference between indoors and outdoors is smaller, and this reduces the heat loss due to ventilation, Q_{air} , from around 44 kWh/m² to 24kWh/m². The conduction heat losses are also lower; in the case of a facade with a U-value of 2.6W/m²K the conduction heat loss decline from 37kWh/m² to 35 kWh/m². Lowering the U-value of the facade from 2.6W/m²K to 1.2W/m²K reduces the conduction heat loss from 51kWh/m² to 32kWh/m², and hence the heating load from 11kWh/m² to 3kWh/m², but it also raises the cooling demand from 15kWh/m² to 23kWh/m². The net effect is zero. In summer, ΔT is 5°C and therefore the heat loss due to ventilation, Q_{air} , falls further to 10kWh/m². The heat loss due to conduction (Q_{cond}) is also reduced, and the solar heat gain is around 29 kWh/m². A lower U-value in the summer reduces the heat loss due to conduction and therefore increases the cooling load.

The effect of the g-value

Lowering the g-value is beneficial in mid-season and summer, but it increases the total load in winter. For example, Table 6.15 shows the effect of g-value on annual energy demand in South-facing offices assuming that $U = 1.2\text{W/m}^2\text{K}$. In winter, when there is a large amount of heat loss due to conduction and ventilation, reducing the g-value unfavourably reduces the heat gain from the sun and in turn increases the heating demand. In mid-season and summer, the results show that cooling demand reduces with a lower g-value, largely because of the associated decrease in solar gains. Annually, using a facade with a g-value of 0.3 instead of 0.5, when the U-value is $1.2\text{W/m}^2\text{K}$ in a South-facing tested office, can save 18kWh/m^2 , which is lower than that found in SC1.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	36	1	-40	-44	29	24	-4
	0.4	31	1	-42	-44	29	35	-7
	0.5	27	3	-44	-44	29	46	-9
M	0.3	7	10	-26	-24	29	28	-5
	0.4	5	16	-29	-24	29	42	-7
	0.5	3	23	-32	-24	29	55	-9
S	0.3	0	38	-9	-3	29	25	-3
	0.4	0	46	-12	-3	29	37	-4
	0.5	0	54	-14	-3	29	49	-6

Table 6.15 Effect of g-value on energy demand of South-facing offices in Caribou, assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC3

6.4 Effect of climate change, SC4

This section investigates the effect of climate change on the energy performance of high-performance facades in offices in Caribou. The future climate file, which is the 2050 medium emission scenario, is used. The standard working scenario is assumed here: 10 working hours per day, 7 days a week, with assumed internal gains of 33.7 W/m² in tested offices. Test results from Tas simulations for Caribou under a climate change scenario are presented and discussed.

Climate change data

Table 6.16 shows the seasonal average values of hourly projected 2050 temperatures and solar irradiation values for Caribou used in the Tas simulations. Compared with Caribou's current weather conditions, the seasonal average outdoor temperatures are predicted to increase by 2.75°C, 2.5°C and 3.725°C in winter, mid-season and summer respectively, and solar radiation by 125kWh/m², 185kWh/m² and 41kWh/m². It can be seen that winter is still the coldest time of the year, with the least amount of solar irradiance, whereas summer is the hottest time of the year, with the highest amount of solar irradiance. The indoor design temperature has been set as 21 degrees Celsius.

Caribou	T _{max}	T _{min}	T _{av}	Solar radiation(Wh/m ²)
Winter	7.7	-15.6	-4.9	3,410
Mid-season	20.1	-5.7	6.4	5,989
Summer	29.7	9.9	19.2	6,822

Table 6.16 Seasonal average temperature and solar radiation data for Caribou, Tas, 2050, medium emission

6.4.1 Caribou annual results, Tas

Figure 6.27 (i, ii, iii, iv) show, respectively for North, South East and West-facing offices in Caribou, the effect of U-values and three levels of g-values on annual energy demand. In general, the annual loads found in SC4 are higher than those in SC1 due to the higher temperatures and solar irradiation values. It can be seen that the results found in SC4 are very similar to those found in SC1, i.e. utilising facades with low U-values, irrespective office orientation, reduces the annual energy demand, except in the case of South-facing offices with $g = 0.5$. The energy reduction effect of lowering the U-value of the facade is more obvious when the facade has a lower g-value of 0.3. Furthermore, lowering the g-value reduces the annual energy demand, and the effect is more obvious in South and West-facing offices.

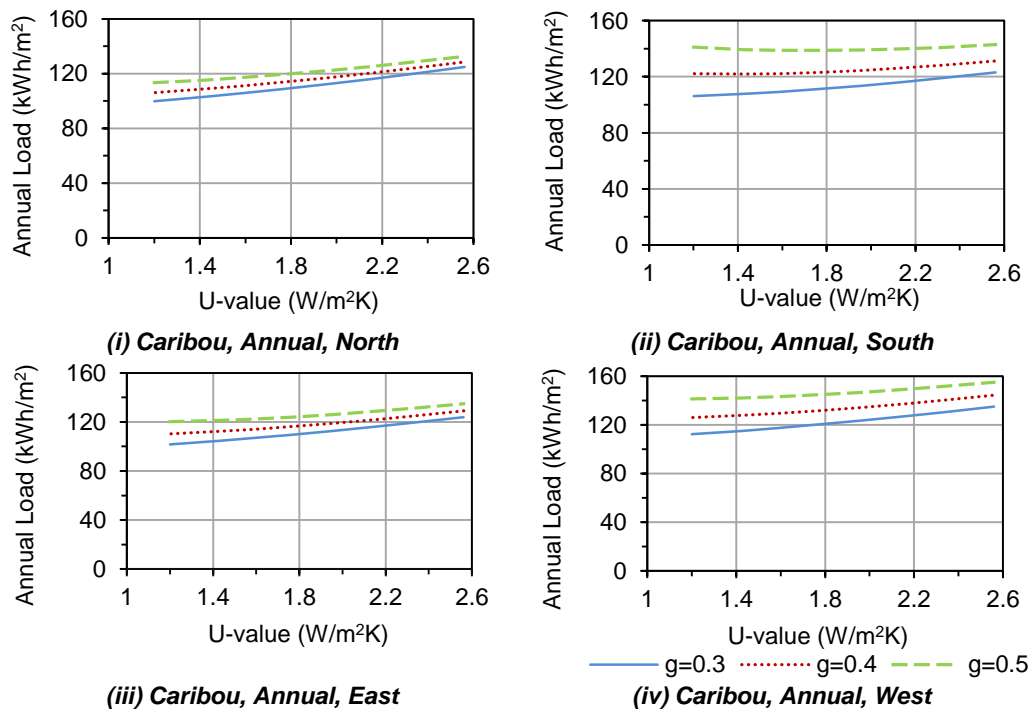


Figure 6.27 Effect of U and g-values and building orientation on annual heating/cooling load of test office using Tas, Caribou, SC4

6.4.2 Seasonal performance of Caribou, Tas

Again, the energy demand by season was determined. Figure 6.28 to Figure 6.30 show the total energy required for offices in winter, mid-season and summer obtained via Tas. Due to the general rise in outdoor temperatures and solar irradiation, the total energy required in winter decreases, but it increases in mid-season and summer.

The results found in summer in SC4 are different from in SC1. It can be seen that similar to SC1, lowering the U-value of the facade reduces energy demand in winter by around 50% (Figure 6.28), irrespective of office orientation, but increases the total load by a small amount in mid-season (Figure 6.29) when $g = 0.4$ and $g = 0.5$, and particularly in a South-facing office. However, in summer (Figure 6.30), lowering the U-value has very little effect on the total load. The effect of lowering the g-value remains the same: it is beneficial in mid-season and summer, and in particular in South and West-facing offices.

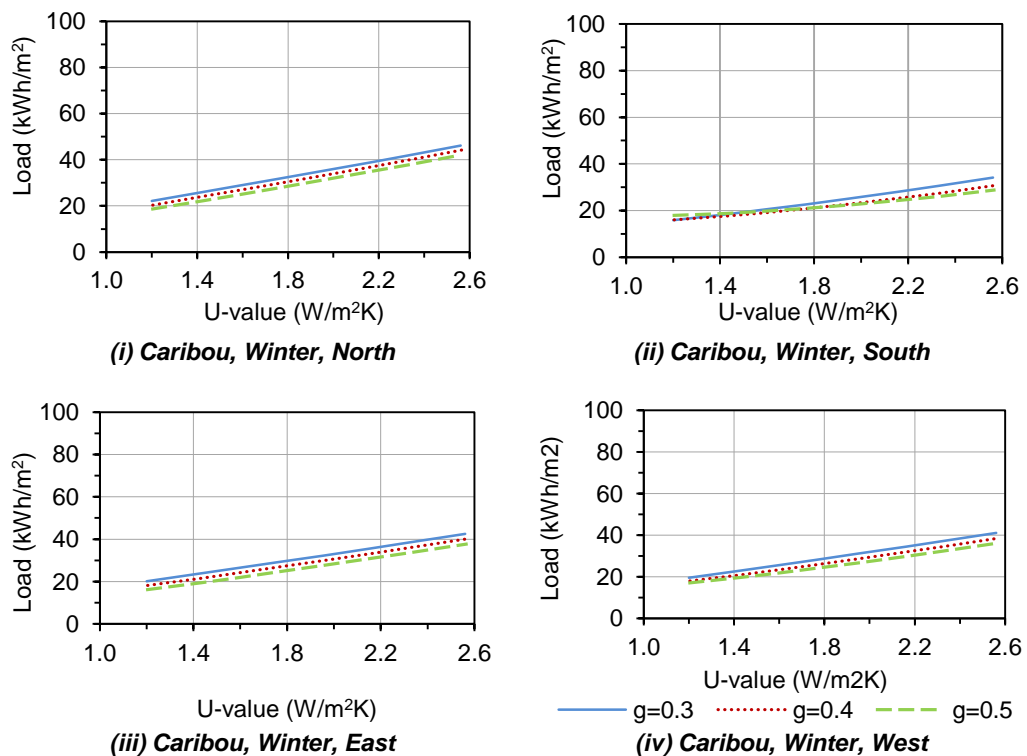


Figure 6.28 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Caribou, SC4

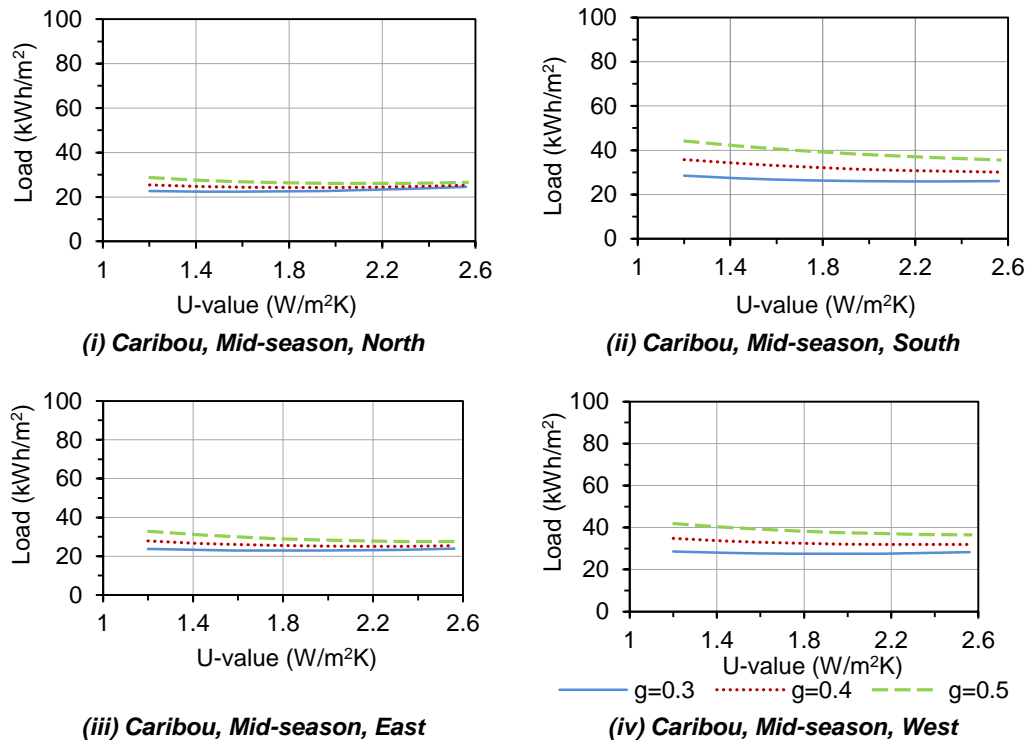


Figure 6.29 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Caribou, SC4

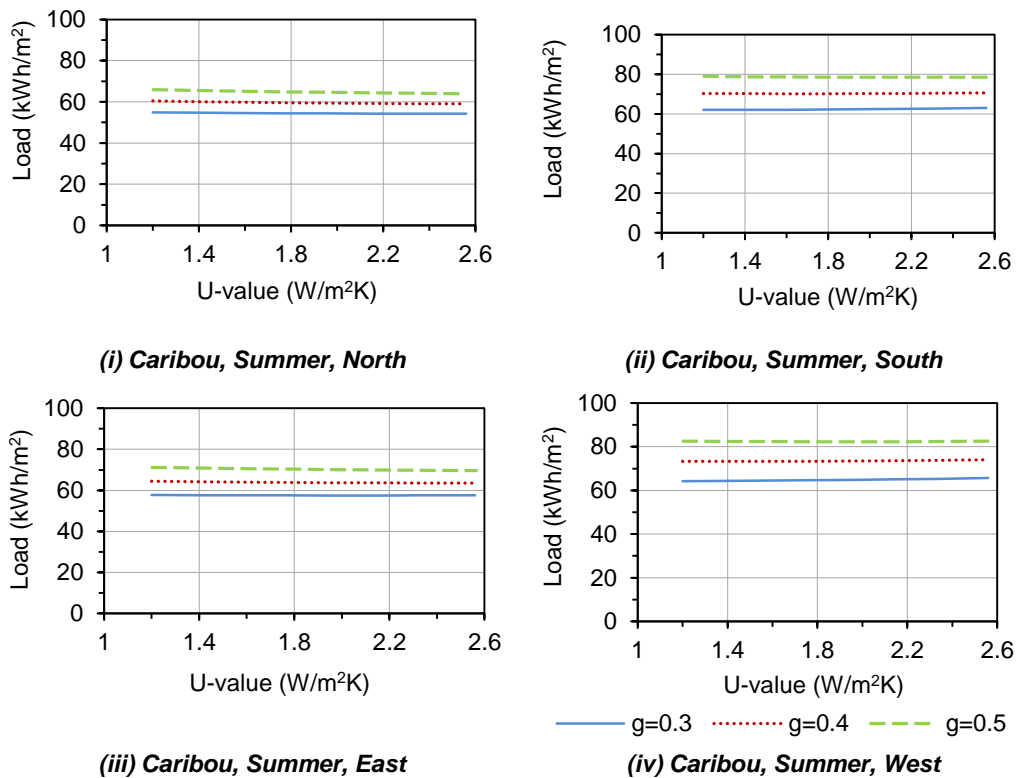


Figure 6.30 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in summer, Caribou, SC4

Figure 6.31 and Figure 6.32 show the nature of the energy usage in offices facing North, South, East and West for winter and mid-season, respectively. In winter, as shown in Figure 6.31, heating is the dominant load in all offices, and there is a small amount of cooling demand in South-facing offices, which increases with decreasing U-value. In mid-season (Figure 6.32), there is a mix of heating and cooling load, and the cooling requirement is higher than the heating requirement in most cases, apart from when the U-value is 2.6W/m²K for North-facing offices. It is also found that, in summer, there is only cooling load, irrespective of office orientation. In all seasons, when the U-value is decreased, the corresponding heating demand decreases but the cooling demand increases.

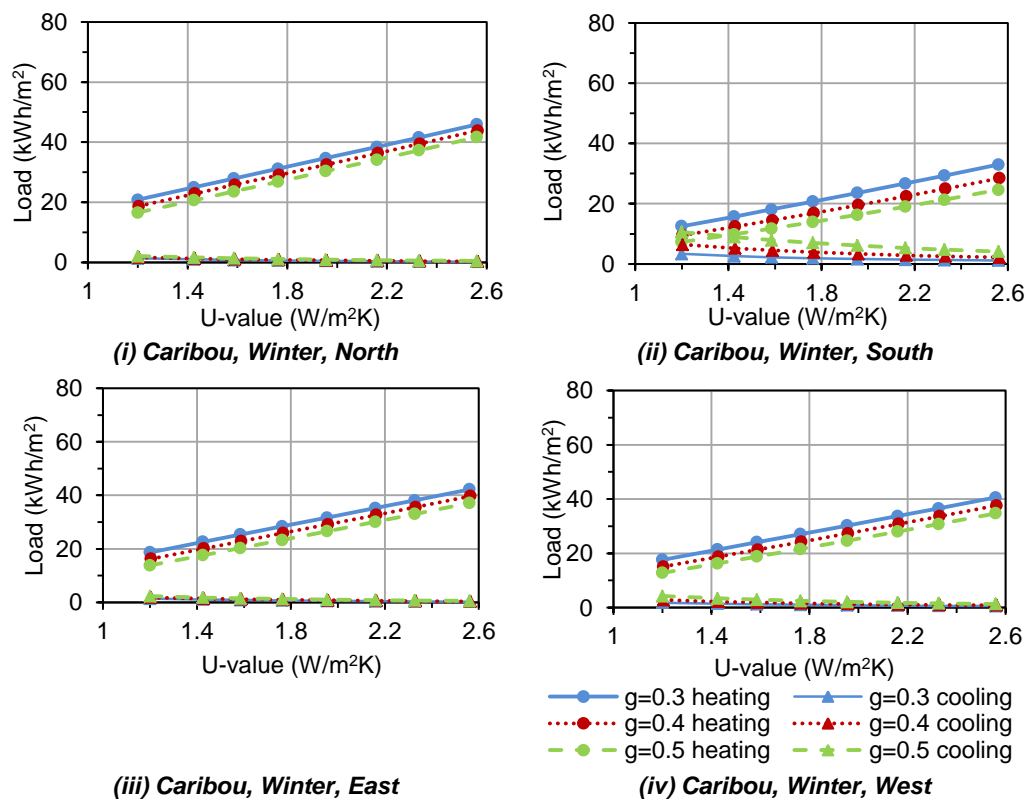


Figure 6.31 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Caribou, SC4

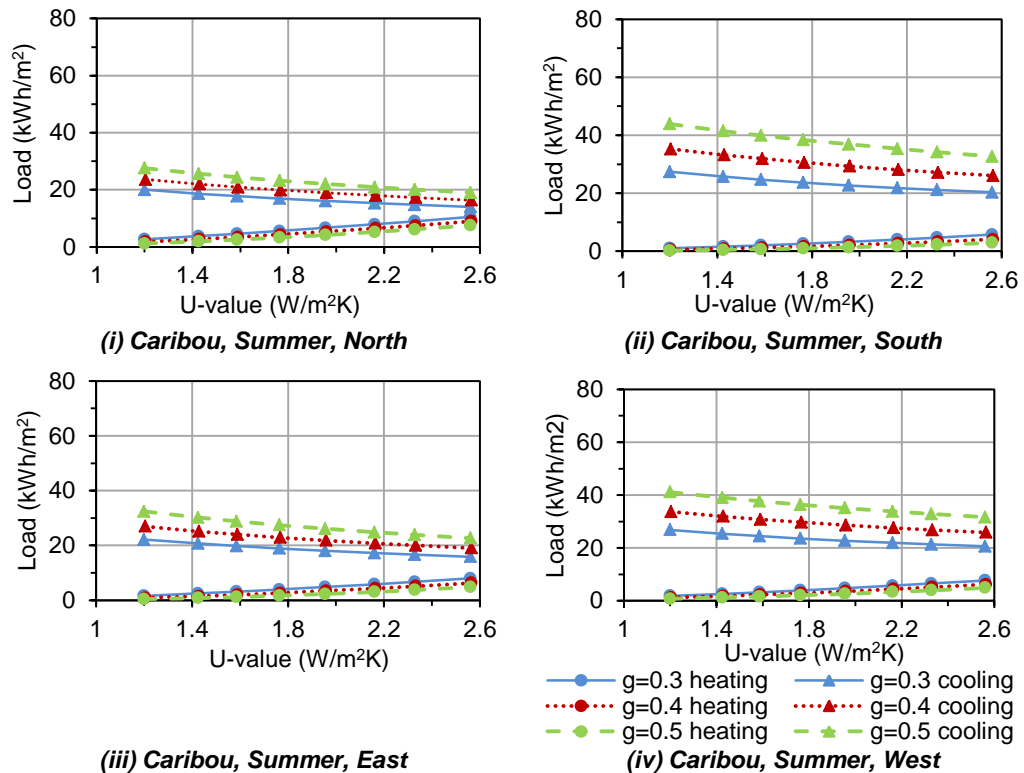


Figure 6.32 Effect of U and g values and building orientation on heating/cooling load of test office using Tas in mid-season, Caribou, SC4

Breakdown of the results

Table 6.17 shows the results for South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and U is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. In SC4, although there is a general increase in the outdoor temperature, outdoors is still colder than indoors throughout the year. The effect of the increased temperature is that there are less heat losses due to conduction and ventilation in all seasons compared with SC1, which tests current weather conditions. Furthermore, the increased level of solar radiation causes a small rise in the solar heat gain.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	7	11	-41	-34	40	47	-9
	2.6	25	4	-71	-34	40	47	-3
M	1.2	0	44	-29	-17	41	56	-8
	2.6	3	33	-46	-17	41	56	-5
S	1.2	0	79	-10	2	41	52	-5
	2.6	0	78	-12	2	41	52	-4

Table 6.17 Effect of U-value on heating/cooling load when $g = 0.5$ for South-facing offices using Tas, Caribou, SC4

Again, the effect of the U-value in each season depends on the temperature and solar irradiance. In winter, the heating demand is highest due to the large ΔT . Lowering the facade's U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ reduces the heat loss and hence the heating requirement (Q_h) from 25kWh/m^2 to 7kWh/m^2 ; it also causes a 6kWh/m^2 increase in the cooling requirement (Q_c). Overall, a facade with $1.2\text{W/m}^2\text{K}$ reduces the total load from 29kWh/m^2 to 18kWh/m^2 .

In mid-season, cooling is dominant. There is a decrease in heat losses from conduction and ventilation, e.g. Q_{air} from 34kWh/m^2 to 17kWh/m^2 , because the ΔT_{av} is smaller. At the same time, solar heat gain (Q_{sol}) increases from 44kWh/m^2 to 53kWh/m^2 . The internal heat gain remains large at 40kWh/m^2 . Overall, there is a net heat gain and hence a cooling requirement. The facade with a lower U-value of $1.2\text{W/m}^2\text{K}$ limits the heat loss due to conduction, which increases the cooling demand.

In summer, the heat gains from the internal environment and the sun are still high leading to a high cooling demand. The outdoor temperature is very close to the indoor level, hence lowering the U-value has very little on the total cooling demand. Annually, using lower U-value facade when $g = 0.5$ increases the annual load in South facing office by a very small amount, which is 2kWh/m^2 , because it reduces the heating demand in winter but increase the cooling demand in mid-season.

Lowering the U-value in the rest of the test offices is beneficial. For example, Table 6.18 shows the values of the principal factors for a North-facing office in winter (W), mid-season (M) and summer (S) assuming $g = 0.5$ and U is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. A North-facing office receives the least amount of solar gain, and therefore has higher heating demand in winter and lower cooling demand in mid-season and summer than a South-facing office. Reducing the U-value of the facade from 2.6 to $1.2\text{W/m}^2\text{K}$ almost halves the heating demand in winter and causes a smaller increase in the total load in mid-season and summer. Overall, lowering the U-value from 2.6 to $1.2\text{W/m}^2\text{K}$ reduces energy demand by 18kWh/m^2 annually.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	1.2	17	2	-40	-34	40	10	9
	2.6	42	0	-72	-34	40	10	15
Mid-season	1.2	1	28	-27	-17	41	22	7
	2.6	7	19	-46	-17	41	22	11
Summer	1.2	0	66	-10	2	41	29	3
	2.6	0	64	-13	2	41	29	5

Table 6.18 Effect of U-value on heating/cooling load when $g = 0.5$ for North-facing offices using Tas, Caribou, SC4

Effect of g-value

Table 6.19 shows the effect of the g-value on seasonal energy demand for a South-facing office, assuming a U-value of $1.2\text{W/m}^2\text{K}$, and Table 6.20 shows the same results for a North-facing office. As in SC1, lowering the g-value reduces the annual energy demand in all offices, especially when the U-value is lower. Furthermore, in winter, lowering the g-value is beneficial in a South-facing office when $U = 1.2\text{W/m}^2\text{K}$, but it increases the total energy demand in the rest of the cases.

Lowering the g-value is beneficial in mid-season and summer, irrespective of the office orientation and U-value, due to the associated reduction in the solar heat gain. Because lowering the g-value significantly reduce the cooling load in mid-season and summer, annually it is always beneficial. In addition, the effect of lowering the g-value is more obvious in offices with higher solar heat gains. For example, lowering the g-value reduces the annual energy demand by 35kWh/m^2 and 13kWh/m^2 in South and North-facing offices, respectively. Hence, the change in the climate assumptions does not change the effect of the g-value.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	13	3	-37	-34	40	25	-4
	0.4	10	6	-39	-34	40	36	-7
	0.5	7	11	-41	-34	40	47	-9
M	0.3	1	27	-23	-17	41	29	-3
	0.4	1	35	-26	-17	41	42	-6
	0.5	0	44	-29	-17	41	56	-8
S	0.3	0	62	-5	2	41	26	-2
	0.4	0	70	-8	2	41	39	-4
	0.5	0	79	-10	2	41	52	-5

Table 6.19 Effect of g-value on energy demand of South-facing offices in Caribou assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC4

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	21	1	-38	-34	40	5	7
	0.4	19	2	-39	-34	40	7	8
	0.5	17	2	-40	-34	40	10	9
M	0.3	3	20	-24	-17	41	12	5
	0.4	2	24	-26	-17	41	17	6
	0.5	1	28	-27	-17	41	22	7
S	0.3	0	55	-6	2	41	15	3
	0.4	0	60	-8	2	41	22	3
	0.5	0	66	-10	2	41	29	3

Table 6.20 Effect of g-value on energy demand of North-facing offices in Caribou assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC4

6.5 Results summary and conclusions

The values used to produce the annual energy demand charts for these four scenarios are shown in Table 6.21. The effect of lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ was calculated as well, and values of annual energy demand are also included in the table. It can be seen that lowering the U-value is always beneficial in Caribou, in particular when the level of internal heat gain is low. The effect is greater than that of lowering the g-value.

		SC1				SC2				SC3				SC4			
	U	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
g=0.3	1.20	92	93	96	103	129	131	137	142	96	95	93	103	100	102	106	112
	1.43	96	96	98	106	133	135	139	145	102	101	97	108	103	105	108	115
	1.59	99	99	100	108	136	137	141	148	106	104	101	112	106	107	109	117
	1.77	102	102	102	111	140	141	144	151	110	109	104	116	109	110	111	120
	1.96	106	105	105	115	145	145	147	156	115	113	109	120	112	113	114	123
	2.16	111	109	108	119	150	150	152	161	121	118	113	126	116	116	117	127
	2.33	115	113	111	122	155	154	156	165	126	123	117	130	120	119	119	130
	2.56	120	118	116	128	163	161	162	172	132	129	123	136	125	124	123	135
	2.6-1.2	28	25	20	25	34	30	25	30	36	33	30	33	25	22	17	23
g=0.4	1.20	98	101	109	115	136	141	153	156	99	100	100	111	106	110	122	126
	1.43	101	103	110	117	139	143	154	159	104	104	103	115	109	112	122	128
	1.59	103	105	110	119	142	145	155	161	108	107	106	119	111	114	122	130
	1.77	106	107	112	121	145	148	156	163	112	111	109	122	114	116	123	132
	1.96	110	110	113	124	149	152	159	167	117	116	112	127	117	119	125	134
	2.16	114	114	116	127	155	156	162	172	122	120	116	131	121	122	126	137
	2.33	117	117	118	131	159	160	165	176	127	124	120	135	124	125	128	140
	2.56	123	121	122	135	166	166	171	182	133	130	125	141	128	129	131	144
	2.6-1.2	25	21	12	20	30	25	18	26	34	31	25	30	22	19	9	18
g=0.5	1.20	106	113	132	133	144	152	171	172	103	105	111	121	113	120	141	141
	1.43	108	113	130	133	146	153	171	173	107	109	113	125	115	121	139	142
	1.59	109	114	129	134	148	155	171	175	110	112	115	128	117	122	139	143
	1.77	111	115	129	135	151	157	172	177	114	115	117	131	119	124	139	145
	1.96	114	117	129	137	155	160	174	180	119	119	119	134	122	126	139	147
	2.16	117	120	130	139	160	163	176	184	124	123	122	139	125	129	140	149
	2.33	120	122	131	142	164	167	178	187	128	127	125	142	128	131	141	152
	2.56	125	126	133	145	170	173	182	193	134	132	130	148	133	135	143	155
	2.6-1.2	19	13	1	13	26	21	11	21	32	27	18	26	19	15	2	14

Table 6.21 Effect of U-value and g-value on annual load, Caribou, Tas

6.5.1 Conclusions

1. Average outdoor temperature in Caribou are below the design indoor temperature throughout the year, particularly in winter, yet there is an overall cooling demand in office buildings because of high internal gains.
2. Energy usage is highest in summer and lowest in winter because of the solar radiation profile in Caribou
3. In general, lowering the U-value reduces the energy required for offices in Caribou, irrespective of office orientation, and even facing uncertainties such as longer working hours, lower internal gains and climate change. This is because a large proportion of the heating demand is reduced by lowering the U-value which decreases the conduction heat loss.
4. Longer occupancy hours increase energy demand because it increases both the annual heating and cooling requirements.
5. When the internal heat gains are reduced, the annual energy demand in offices increases by a small amount because of the cold climate.
6. Climate change will result in higher outdoor temperatures and solar irradiation levels which in combination increase energy demand because of reduced conduction heat losses and higher solar gains.
7. Lowering g-value of facades increases the energy demand in winter but reduces the energy demand in mid-season and summer. It is more beneficial when the U-value is lower and in South facing offices. Its energy reduction effect is less than lowering the U-value.
8. The office annual energy demand is the lowest when a low U and low g-values facade is used.

CHAPTER 7 INFLUENCE OF HIGH-PERFORMANCE FACADES ON ENERGY USAGE IN ABU DHABI OFFICES

This chapter investigates the influence of high-performance facades on energy usage in office buildings in Abu Dhabi. The same four scenarios are assessed, but scenario 4 (SC4) now considers the climate predicted for Abu Dhabi in 2050; the test programme is outlined in Table 7.1. For SC1 and SC2, preliminary tests using the steady-state method are carried out alongside the Tas simulation, in order to ensure the results from the Tas simulation are reasonable.

Hence, results from the steady-state method are presented first, followed by the Tas results. In each case, the heating/cooling load is calculated assuming the use of facades' U-values between $1.2\text{W/m}^2\text{K}$ and $2.6\text{W/m}^2\text{K}$, and g-values from 0.3 to 0.5. All steady-state tests are carried out only for South and West-facing offices due to the data availability, as explained in Chapter 3. All Tas simulation tests are performed on offices facing North, East, South and West.

Fixed conditions						
Test location: Abu Dhabi						
Ventilation rate: 10 litres per person per second (<i>l/p/s</i>)						
WWR: 0.7						
Indoor temperature: 22°C						
Test variables and methods						
Code	U-value ($\text{W/m}^2\text{K}$)	g-value	Orientations & modelling tools	Working schedule	Internal gains (W/m^2)	Climate (CIBSE)
SC1	1.2 – 2.6	0.3, 0.4, 0.5	S, W (steady- state) N, S, E, W (Tas)	0800-1800 (10 hrs)	33.7	Current
SC2	1.2 – 2.6	0.3, 0.4, 0.5	S, W (steady- state) N, S, E, W (Tas)	0700-2300 (16 hrs)	33.7	Current
SC3	1.2 – 2.6	0.3, 0.4, 0.5	S, W (steady- state) N, S, E, W (Tas)	0800-1800 (10 hrs)	25	Current
SC4	1.2 – 2.6	0.3, 0.4, 0.5	S, W (steady- state) N, S, E, W (Tas)	0800-1800 (10 hrs)	33.7	Future 2050

Table 7.1 Test summary for Abu Dhabi

As in Chapter 4, for each scenario the influence of U and g-values of facades on the annual energy performance of offices is discussed first followed by the seasonal total energy demand results. Further insight is provided by presenting the numerical values of the principal factors influencing the energy demand. At the end of the chapter, a summary table of numerical results used to produce the annual graphs is provided, in order to quantify the effect of the U and g-values and for ease of comparison.

7.1 Influence of high-performance facade in Abu Dhabi offices, SC1

This section presents the test results for Abu Dhabi, assuming the standard working hours scenario (SC1). The test results from the steady-state method are presented and discussed first, followed by the more detailed and accurate results obtained from the Tas simulations.

7.1.1 Steady-state study

Climate data

Table 7.2 shows the seasonal average values of outdoor dry-bulb temperature, design indoor temperature, the temperature difference between indoors and outdoors, and the solar irradiance values for South and West orientations. As previously noted, winter covers the period November-February, summer June-September and the remaining months are classed as mid-season.

Abu Dhabi has a hot climate; during winter, T_{out} is 20.6°C, which is the lowest in the year, rising to 27°C and 33.6°C in mid-season and summer respectively. T_{in} is set at 22°C, therefore in winter outdoors is colder than indoors by 1.4°C, indicated by the negative ΔT value. However, outdoors is hotter than the indoors by 5°C and 11.6°C in mid-season and summer respectively. For South orientation facades, the solar irradiance level is at its highest during the winter months and lowest in the summer. However, the trend is opposite for West orientation. These seasonal values show that each season has its own climate features in terms of temperatures and solar irradiance.

Abu Dhabi	T_{out} (°C)	T_{in} (°C)	ΔT (°C)	S_0 , (W/m ²)			
				N	E	S	W
Winter	20.6	22	-1.4	-	-	189.8	106.5
Mid-season	27.0	22	5.0	-	-	125.0	140.0
Summer	33.6	22	11.6	-	-	96.6	148.0

Table 7.2 Abu Dhabi indoor and outdoor temperatures (°C), solar irradiance (W/m²), averaged by seasons

T_{in} = seasonal averaged daily average indoor design temperature (°C)

T_{out} = seasonal averaged daily average outdoor dry-bulb temperature (°C)

$\Delta T = T_{out} - T_{in}$ (°C)

S_0 = seasonal averaged daily average solar irradiance (W/m²)

Annual results

Figure 7.1 (i, ii) shows the effect of the U-value and g-value on annual energy demand in offices facing South and West, obtained by the steady-state calculation method, under the SC1 condition. It can be seen that lowering the U-value reduces the annual energy demand by around 30kWh/m² in the test offices facing in both orientations. The annual energy demand in South-facing offices is slightly higher than that in West-facing ones. Lowering the g-value from 0.5 to 0.3 has a larger effect in reducing the annual energy demand than lowering the U-value. Overall, it can be seen that annual energy demand is the lowest when the offices are using $g = 0.3$ and $U = 1.2\text{W/m}^2\text{k}$ facades.

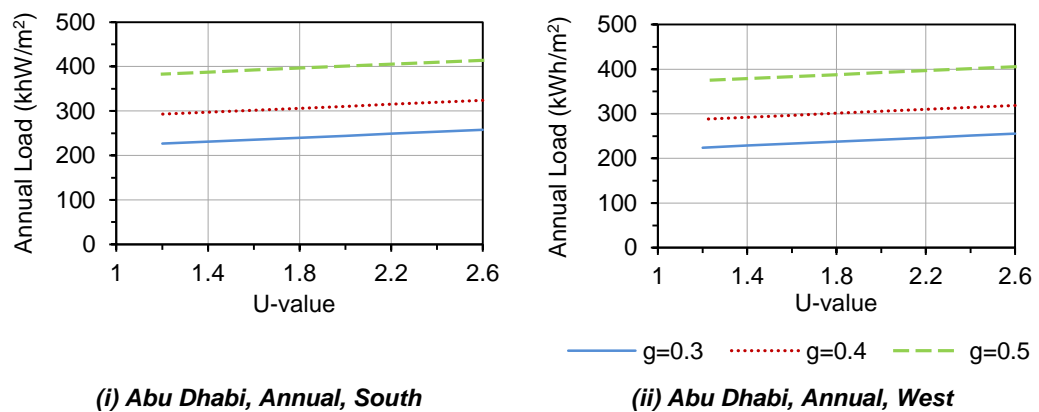


Figure 7.1 Effect of U and g-values and building orientation on annual load of test offices using steady-state calculation, Abu Dhabi, SC1

Seasonal Abu Dhabi results: steady-state

The seasonal trends were studied in order to understand the annual results. Figure 7.2 to Figure 7.4 show the heating/cooling loads estimated for South and West-facing test offices in winter, mid-season and summer respectively. A positive number in the figure indicates that there is an overall net heat gain and represents the amount of the cooling load. Conversely, a negative number indicates an overall net heat loss, giving the amount of the heating load, with both loads given in kWh/m².

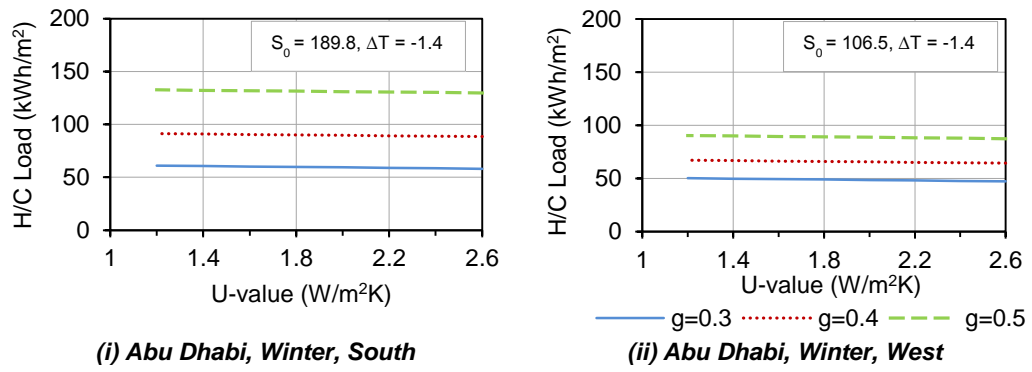


Figure 7.2 Effect of U and g-values and building orientation on heating/cooling load of test offices using steady-state calculation in winter, Abu Dhabi, SC1

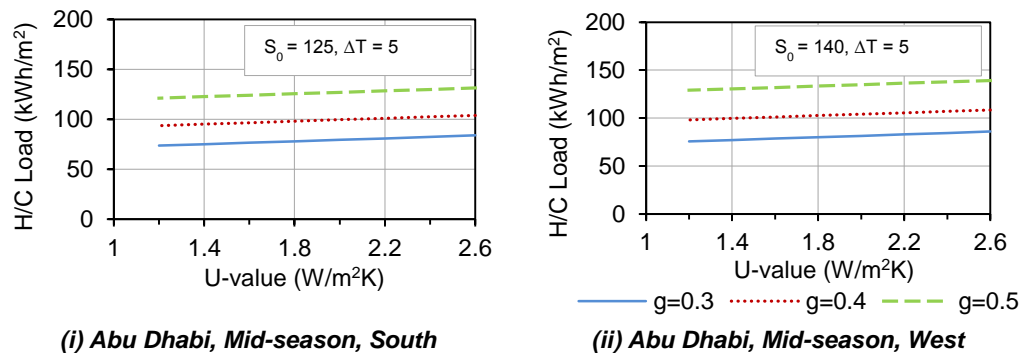


Figure 7.3 Effect of U and g-values and building orientation on heating/cooling load of test offices using steady state calculation in mid-season, Abu Dhabi, SC1

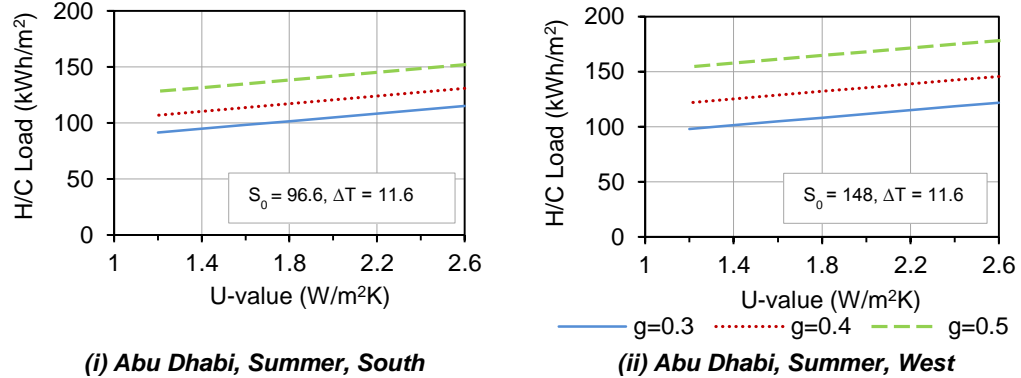


Figure 7.4 Effect of U and g values and building orientation on heating/cooling load of test office using steady state calculation in summer, Abu Dhabi, SC1

It can be seen that there are only cooling requirements in the test offices all year round, indicated by the positive results. In winter utilising a low U-value facade increases the cooling need slightly, but it reduces the cooling need in both mid-season and summer, irrespective of the office orientation. Lowering the g-value of the facade reduces the cooling needs in the test offices all year around; its effect is larger when S_0 is higher. Furthermore, it can be seen that South-facing offices require a larger amount of cooling than West-facing offices in winter, but the opposite is required in summer. It is surprising to find that, even though cooling is required for the whole year, the effect of

lowering the U-value in winter is different from that during the rest of the year, whereas lowering the g-value always reduces the cooling demand.

Breakdown of the results

Further insights can be obtained by looking at the values obtained for each individual term of the heat balance equation for each season. Table 7.3 shows the results for West and South-facing offices in winter (W), mid-season (M) and summer (S), assuming that $g = 0.5$ and the U-value is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$. Additionally, Table 7.4 shows the results assuming $g = 0.3$. A negative number indicates that there is a heat loss or a heating demand, and vice versa.

	U	West					South				
		Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}
W	1.2	134	-3	-2	41	97	91	-3	-2	41	55
	2.6	131	-5	-2	41	97	88	-5	-2	41	55
M	1.2	121	9	7	41	64	129	9	7	41	72
	2.6	132	19	7	41	64	139	19	7	41	72
S	1.2	128	20	17	41	50	154	20	17	41	76
	2.6	152	44	17	41	50	178	44	17	41	76

Table 7.3 Effect of U-value on energy demand of West and South-facing offices in Abu Dhabi assuming $g = 0.5$, steady-state, SC1

During the winter months ΔT is -1.4°C , so the amount of heat loss due to conduction and ventilation is low compared with the amount of heat gain from the sun and the internal heat gain. Consequently, there is high cooling demand, and lowering the U-value of the facade decreases the heat loss due to conduction. This in turn increases the total cooling demand slightly for offices facing in both orientations.

Outdoors is warmer than indoors for the rest of the year, hence there are heat gains from conduction and ventilation. In mid-season, ΔT rises to 5°C ; and lowering the U-value of the facade reduces the unwanted conductive heat gain into indoors and hence reduces the cooling demand in the test offices. In summer, ΔT increases further to 11.6°C , hence the reduction in the unwanted heat gain due to lowering the U-value of the facade is larger; this is reflected in the larger gradients of the trend-lines in Figure 7.4.

Although the amount of solar heat gain is different in offices facing South and West, it is generally higher than the rest of the terms of the equation when $g = 0.5$. Looking at Table 7.4, when the g-value is lowered to 0.3, the solar heat gain falls significantly. By comparing Table 7.3 and Table 7.4, which show the effect of lowering the g-value from 0.5 to 0.3, it can be seen that the rest of the terms (Q_{cond} , Q_{air} and Q_{int}) remain the same

in both cases. Therefore, lowering the g-value of the facade can reduce the seasonal and annual cooling demand in all test offices due to the decrease in solar heat gain. Furthermore, the effect of lowering the g-value is larger when the solar irradiance level is higher. For instance, this can be seen in a West-facing office in winter compared with summer.

		West					South				
	U	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}
W	1.2	62	-3	-2	41	25	51	-3	-2	41	14
	2.6	59	-5	-2	41	25	48	-5	-2	41	14
M	1.2	74	9	7	41	16	76	9	7	41	18
	2.6	84	19	7	41	16	86	19	7	41	18
S	1.2	91	20	17	41	13	98	20	17	41	20
	2.6	115	44	17	41	13	122	44	17	41	20

Table 7.4 Effect of U-value on energy demand of West and South facing offices in Abu Dhabi assuming $g = 0.3$ using steady-state, SC1

7.1.2 Annual results, Tas

Climate Data

Table 7.5 shows the seasonal average values of climate data used in the Tas simulations. It can be seen that winter is the coldest time of the year with the least amount of solar irradiance, whereas summer is the hottest time of the year with the greatest amount of solar irradiance. The indoor design temperature is set as 22°C, hence the indoor design temperature is slightly higher than the average outdoor temperature in winter, but lower in mid-season and significantly lower in summer.

Abu Dhabi	$T_{max}(^{\circ}C)$	$T_{min}(^{\circ}C)$	$T_{av}(^{\circ}C)$	S (Wh/m ²)
Winter	30.7	11.1	20.6	7,062
Mid-season	38.0	17.9	27.0	8,070
Summer	44.2	24.0	33.2	8,949

Table 7.5 Seasonal averaged temperature and solar radiation data for Abu Dhabi, 2050

Annual results

Figure 7.5 (i, ii, iii, iv) shows respectively for North, South, East and West facing offices in Abu Dhabi the effect of the U and g-value on annual energy demand obtained by means of Tas. The annual energy demand in the test offices was found to range between 220kWh/m² and 340kWh/m², and it is higher in South and West-facing than in North and East-facing offices. It can be seen that utilising facades with a low U-value reduces the annual energy demand in all three levels of g-values, by around 6% in all of the test offices. Lowering the g-value from 0.5 to 0.3 can lower the annual energy demand of the test offices, irrespective of the U-value and orientation. Additionally, the amount of energy reduction by lowering the g-value is higher in South and West-facing offices. Overall, it can be seen that the test offices using a lower g-value (0.3) and lower U-value facade have the lowest annual energy demand for all orientations.

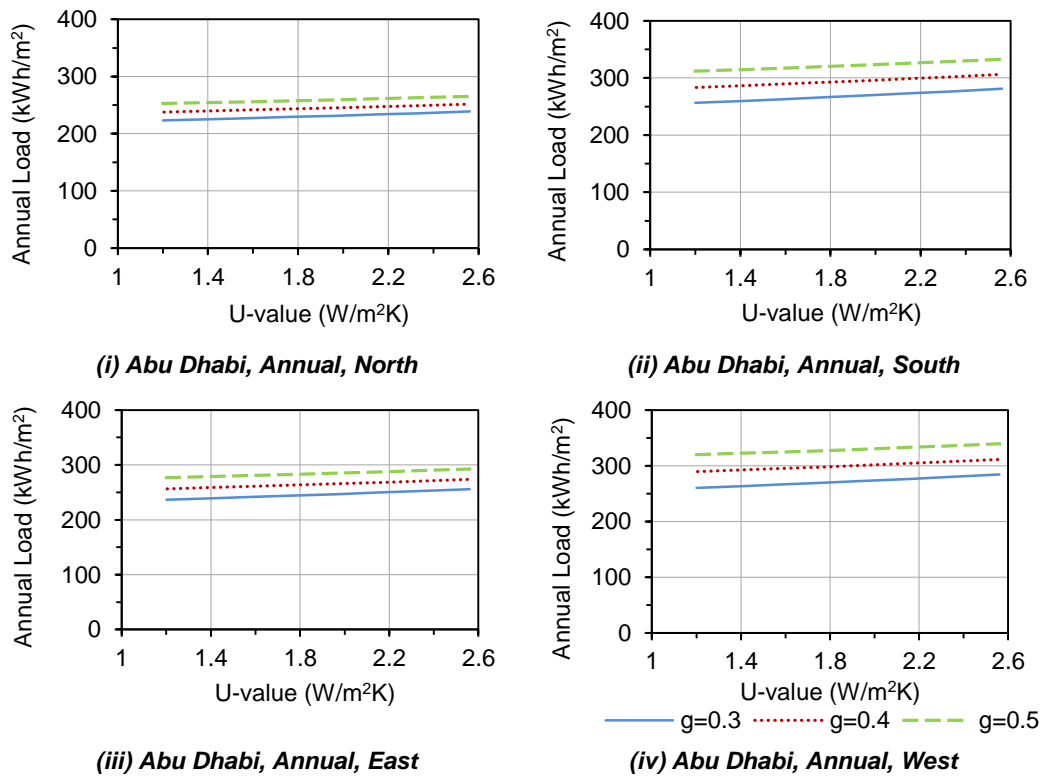


Figure 7.5 Effect of U and g values and building orientation on annual heating/cooling load of test office Tas, Abu Dhabi, SC1

7.1.3 Seasonal results: Tas

In order to understand the annual trends, the energy demand by season is determined and is shown in Figure 7.6 (winter), Figure 7.7 (mid-season) and Figure 7.8 (summer). The simulation results used for generating Figure 7.6 to Figure 7.8 show that all of the test offices only have cooling requirements all year around. The cooling requirements in winter are the lowest, ranging between 50kWh/m² and 100kWh/m², in mid-season the range is between 70kWh/m² and 120kWh/m², and 90kWh/m² to 150kWh/m² for summer. In winter, a South-facing office requires more cooling energy than the test offices facing the other orientations. Additionally, in summer the West-facing office has the highest cooling demand.

The effect of lowering the U-value of the facade differs for all seasonal periods, while the effect of lowering the g-value is more consistent. In winter, lowering the U-value has little effect on the cooling demand in all test offices. However, during mid-season, lowering the U-value can reduce the office cooling loads slightly, and the benefit is more obvious in summer. For all the seasons, lowering the g-value from 0.5 to 0.3 reduces the energy demand in both the South and West-facing offices, but the effect is smaller in the test offices facing North and East.

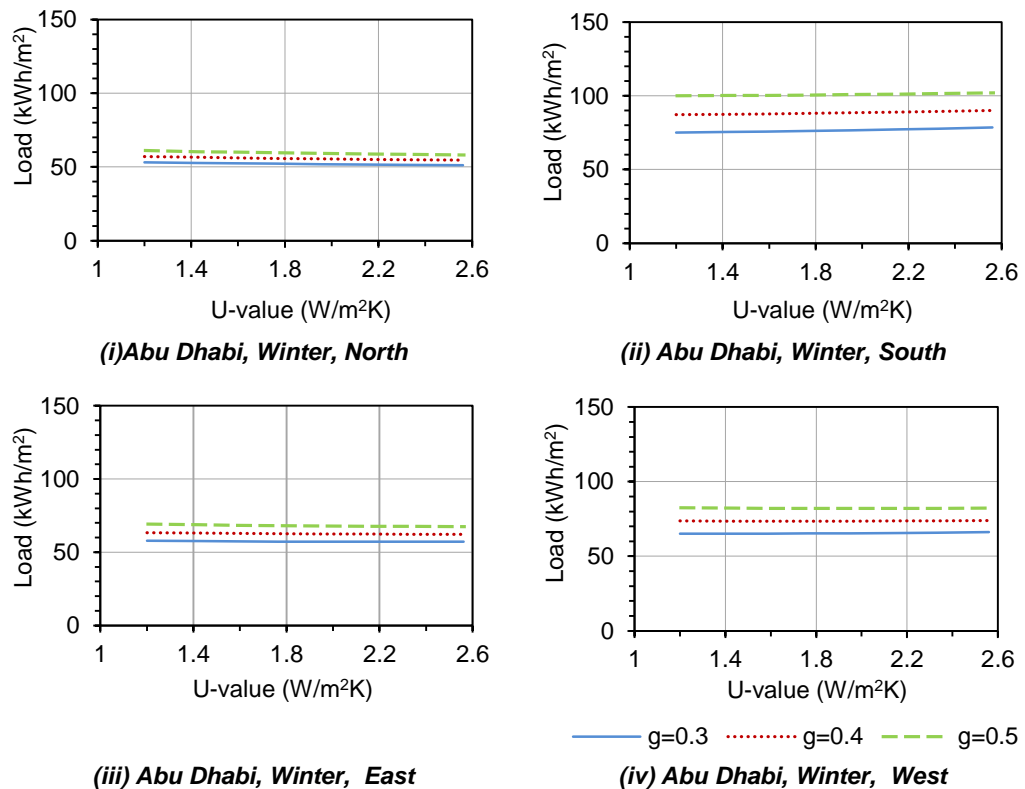


Figure 7.6 Effect of U and g values and building orientation on heating/cooling load of test office using Tas in winter, Abu Dhabi, SC1

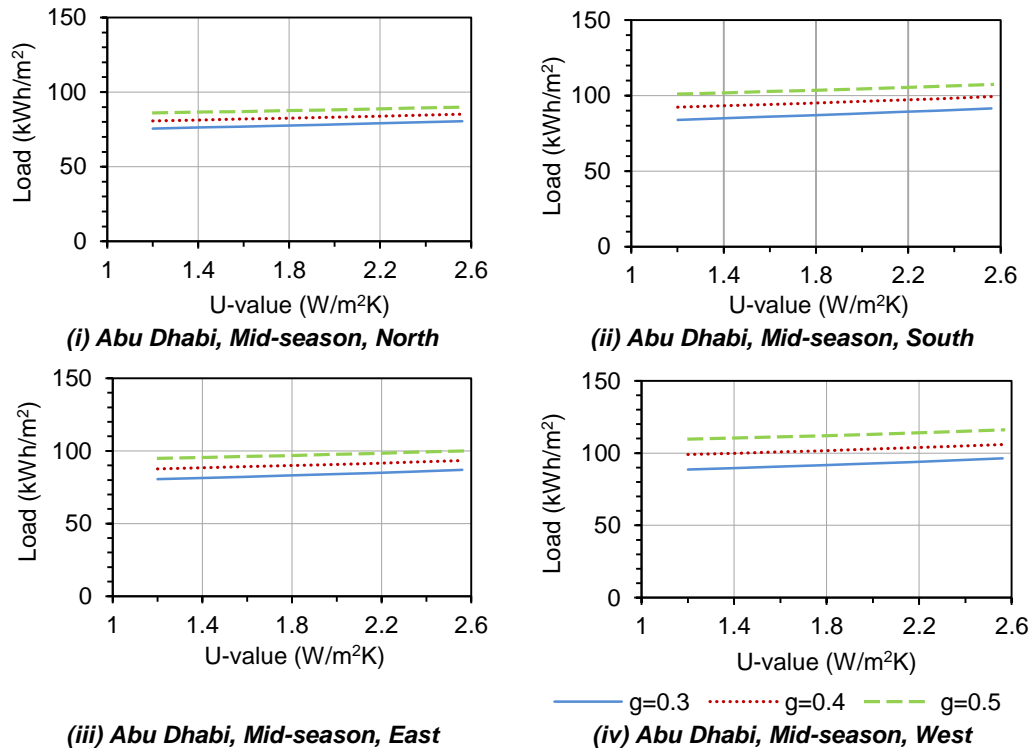


Figure 7.7 Effect of U and g values and building orientation on heating/cooling load of test office using Tas in mid-season, Abu Dhabi, SC1

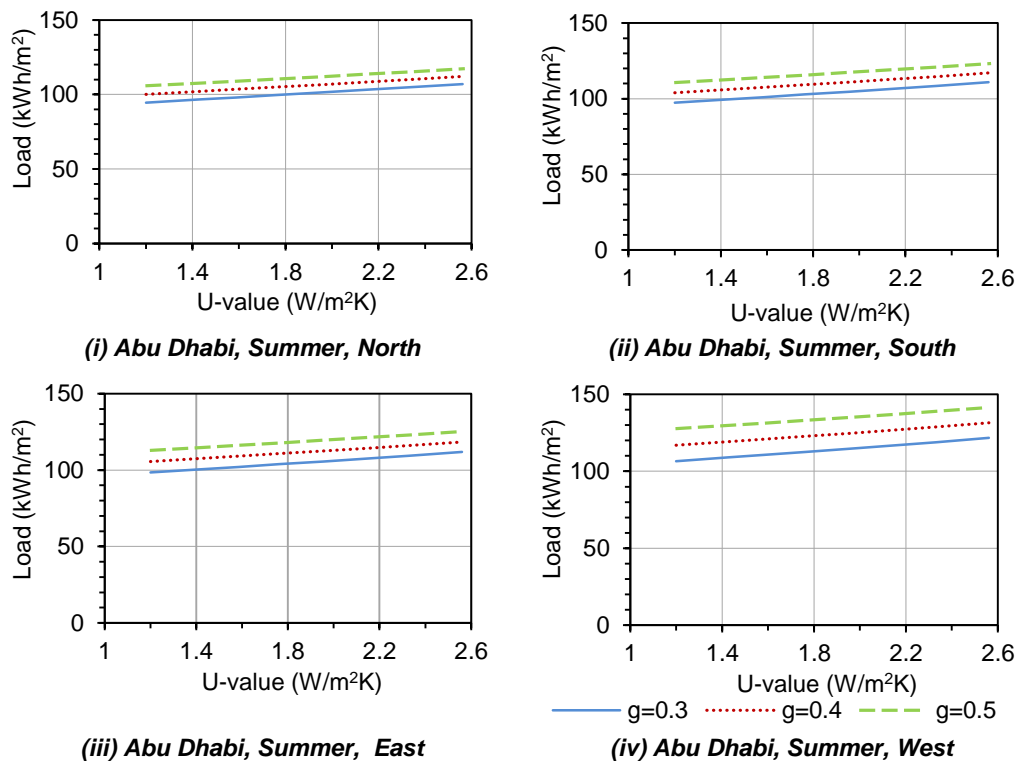


Figure 7.8 Effect of U and g values and building orientation on heating/cooling load of test office using Tas in summer, Abu Dhabi, SC1

Breakdown of the results

Again, further insights are obtained by considering values of the principal factors influencing energy demand, namely:

- Conduction heat gain/loss through facade (Q_{cond})
- Ventilation heat gain/loss (Q_{air})
- Internal heat gain (Q_{int})
- Solar heat gain (Q_{sol})
- Heat gain/loss from adjacent spaces due to building heat transfer (Q_b)

Note that Q_h and Q_c represent respectively the heating and cooling load in kWh/m². Q_b measures the heat gain/loss through internal building elements e.g. walls, floors, ceilings and heat temporarily stored in the air (EDSL 2015). Q_b is not discussed within these results, since the difference it makes is small compared with the other components of the heat balance; additionally, it does not affect the overall trends. This applies to all the following cases in this chapter.

Looking at the values of the principal factors by season, as shown in Table 7.6 for South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and U as either 1.2 W/m²K or 2.6 W/m²K, it can be seen that the amount of solar heat gain is highest during winter months and the lowest in summer. Heat gain due to ventilation is lowest in winter but highest in summer due to the variations in the outdoor dry-bulb temperature. In general, the heat gains from the sun and the internal environment are high, and there are also some heat gains due to ventilation. These factors lead to high cooling requirements in the test offices throughout the year, and the summer cooling loads in the test offices are the highest due to this extra heat gain from both conduction and ventilation.

The effect of the U-value depends on the outdoor dry-bulb temperature, which determines the amount of conduction heat loss/gain. In winter, lowering the U-value from 2.6 to 1.2W/m²K has little effect on the conduction heat loss because the outdoor temperature is close to the indoor design temperature. The values for other components are the same for both of the U-value cases, hence their cooling requirements are almost the same. During mid-season, the outdoor air is hotter than the indoor design temperature by roughly 2°C; this causes heat gain rather than loss from conduction. Lowering the U-value of a facade limits the unwanted conduction heat gains and therefore can reduce the cooling demand by around 6kWh/m².

The effect of lowering the U-value is most noticeable in the summer, when the outdoor temperature is the highest in the year and is hotter than the indoor design temperature by 8°C. Lowering the U-value can then reduce the heat gain due to conduction by 14kWh/m², and in turn the seasonal cooling requirement, from 123kWh/m² to 111kWh/m². It should be noted that the solar heat gain obtained by the South-facing office is highest in winter but lowest in summer; the same result was found using the steady-state calculation.

	U	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	1.2	0	100	-12	3	40	83	-14
	2.6	0	102	-10	3	40	83	-14
M	1.2	0	101	-2	13	41	51	-2
	2.6	0	107	5	13	41	51	-3
S	1.2	0	111	9	23	41	37	1
	2.6	0	123	23	23	41	37	0

Table 7.6 Effect of U-value on energy demand of South facing offices in Abu Dhabi assuming $g = 0.5$, SC1

Table 7.7 shows the effect of lowering the U-value from 2.6 to 1.2 W/m²K on the values of seasonal energy demand and the principal factors in a North-facing office. When compared with the values of a South-facing office (Table 7.6), it can be seen that the influence of lowering the U-value is almost the same apart from the winter case. During winter, it increases the cooling requirement, but it can reduce the cooling demand in mid-season and summer because it limits the unwanted heat gain. A North-facing office generally has lower cooling demand in all seasons as it receives a lower solar heat gain, which also is the reason for the major difference between North and South-facing offices. It should be noted that the heat gain due to ventilation is the same.

	U	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	1.2	0	61	-9	3	40	14	13
	2.6	0	58	-14	3	40	14	15
M	1.2	0	86	-1	13	41	25	7
	2.6	0	90	3	13	41	25	8
S	1.2	0	106	9	23	41	29	4
	2.6	0	117	22	23	41	29	3

Table 7.7 Effect of U-value on energy demand of North-facing offices in Abu Dhabi assuming $g = 0.5$, SC1

Effect of g-value

From the annual results, it can be seen that facades with lower g-values have lower energy requirements in Abu Dhabi. Additionally, the seasonal results show that this is true for all office orientations and seasons. Table 7.8 shows the effect of lowering the g-value of the facade from 0.5 to 0.3 on the seasonal cooling demand in South facing offices. It can be seen in Table 7.8 that energy demand reduces with a lower g-value, largely because of the decrease in solar gains. Lowering the facade g-value from 0.5 to 0.3, when $U = 1.2\text{W/m}^2\text{K}$ in a South-facing tested office, reduces the cooling demand by 25kWh/m^2 , 17kWh/m^2 and 14kWh/m^2 for winter, mid-season and summer respectively. Therefore, it can reduce the annual energy demand by 56kWh/m^2 , which is larger than the cooling reduction that can be made by lowering the U-value.

		Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	0.3	0	75	-5	3	40	43	-6
	0.4	0	87	-8	3	40	62	-10
	0.5	0	100	-12	3	40	83	-14
Mid-season	0.3	0	84	3	13	41	26	1
	0.4	0	92	1	13	41	38	-1
	0.5	0	101	-2	13	41	51	-2
Summer	0.3	0	97	12	23	41	19	2
	0.4	0	104	11	23	41	28	2
	0.5	0	111	9	23	41	37	1

Table 7.8 Effect of g-value on energy demand of South-facing offices in Abu Dhabi assuming $U = 1.2\text{ W/m}^2\text{K}$, Tas, SC1

Table 7.9 shows the effect of lowering the g-value of the facade from 0.5 to 0.3 on the seasonal cooling demand in North-facing offices. Lowering the facade g-value from 0.5 to 0.3 when $U = 1.2\text{W/m}^2\text{K}$ in a North facing tested office can reduce the cooling demand by 8kWh/m^2 , 10kWh/m^2 and 11kWh/m^2 for winter, mid-season and summer respectively, due to the decrease in the solar heat gain. The heat gain due to ventilation is the same in both North and South-facing offices, whereas there is a small difference between the amounts of conduction heat gain/loss.

		Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	0.3	0	53	-7	3	40	7	10
	0.4	0	57	-8	3	40	11	11
	0.5	0	61	-9	3	40	14	13
Mid-season	0.3	0	76	2	13	41	13	6
	0.4	0	81	1	13	41	19	7
	0.5	0	86	-1	13	41	25	7
Summer	0.3	0	95	12	23	41	15	4
	0.4	0	100	11	23	41	22	4
	0.5	0	106	9	23	41	29	4

Table 7.9 Effect of g-value on energy demand of South-facing offices in Abu Dhabi assuming $U = 1.2\text{W/m}^2\text{K}$, T_{as} , SC1

7.2 Abu Dhabi: effect of prolonged office working hours, SC2

This section presents the test results for Abu Dhabi under a prolonged working hour scenario (SC2). The scenario considers 16 working hours per day, 7 days a week, with assumed internal gains of 33.7W/m^2 in tested offices under Abu Dhabi's current climate conditions. The test results from using the steady-state method are presented and discussed first, followed by the more detailed and accurate results obtained from the T_{as} simulations.

7.2.1 Steady-state study

Figure 7.9 (i, ii) shows the effect of the U-value and g-value on the annual energy demand in the test offices facing South and West, obtained by the steady-state calculation method under the SC2 condition. The annual energy demand in the test offices in SC2 increases to between 300kWh/m^2 and 500kWh/m^2 compared with the steady-state annual results in SC1. The effect of lowering the U-value remains the same in SC2: it can reduce the annual energy demand by around 30kWh/m^2 in all test offices irrespective of orientations. Lowering the g-value from 0.5 to 0.3 has a larger effect in reducing the annual energy demand in the test offices than lowering the U-value. Overall, it can be seen that the test offices using a lower g-value (0.3) and a lower U-value ($1.2\text{W/m}^2\text{k}$) facade have the lowest annual energy demand.

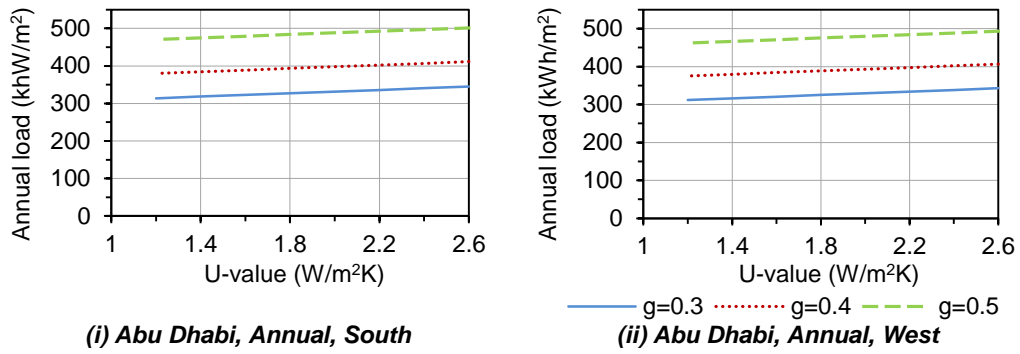


Figure 7.9 Effect of U and g-values and building orientation on annual heating/cooling load of test office using steady-state calculation, Abu Dhabi, SC2

Seasonal results

The seasonal trends found in SC2 are the same as in SC1. The energy demand by season is determined and shown in Figure 7.10 (winter), Figure 7.11 (mid-season) and Figure 7.12 (summer). It can be seen that there are cooling requirements in the test offices all year around, but the results observed are different in winter and the rest of the year. Although low U-value facades do not have much beneficial effect in winter, they have an energy reduction effect in both mid-season and summer. Lowering the g-value of the facade always reduces the cooling requirements. Furthermore, the annual results follow the prevailing patterns for the three seasons.

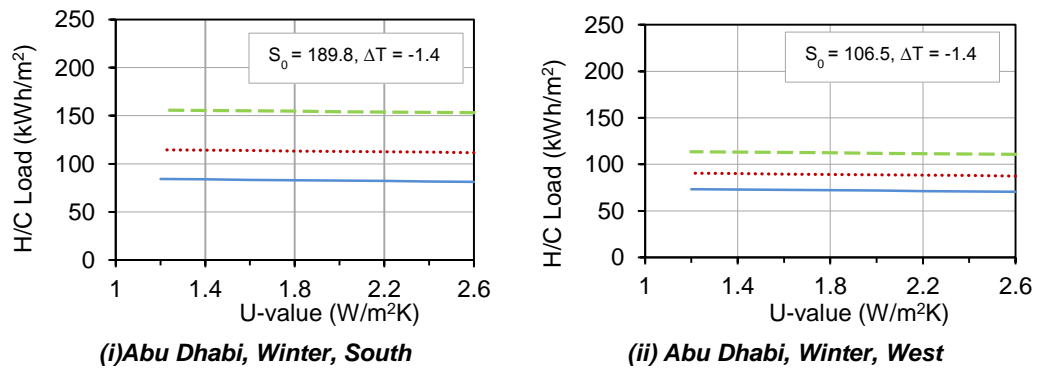


Figure 7.10 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in winter, Abu Dhabi, SC2

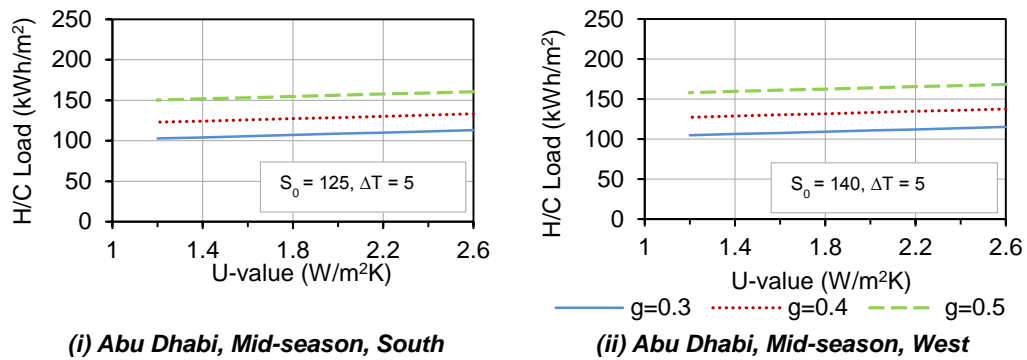


Figure 7.11 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in mid-season, Abu Dhabi, SC2

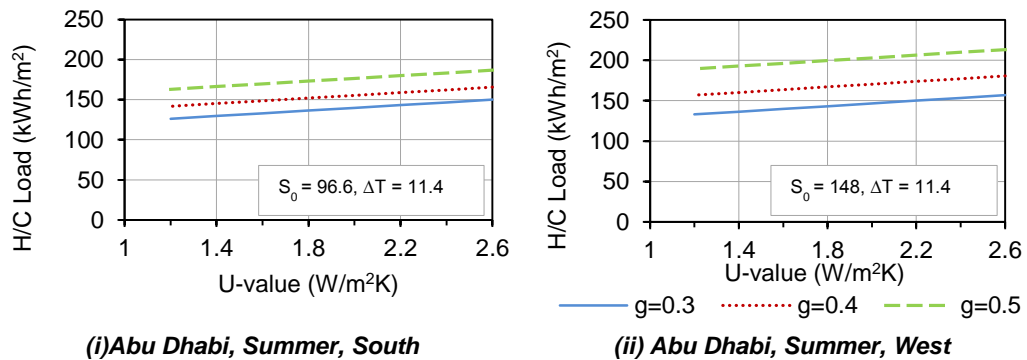


Figure 7.12 Effect of U and g-values and building orientation on heating/cooling load of test office using steady-state calculation in summer, Abu Dhabi, SC2

Breakdown of the results

Although there is generally a higher cooling requirement in all test offices, the reasons behind the different seasonal results remain the same in SC2 and SC1. Table 7.10 shows the results for North and South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and the U-value is either $1.2\text{W/m}^2\text{K}$ or $2.6\text{W/m}^2\text{K}$, Table 7.11 shows the results assuming $g = 0.3$. A negative number indicates there is a heat loss or heating demand in the tested office, and vice versa.

It can be seen that, due to the longer working hours, the internal heat gain rises from 41kWh/m^2 to 66kWh/m^2 and there is also a relatively smaller increase in the heat gain/loss due to ventilation. The remaining terms stay the same in SC2. Hence, there is a general rise in the cooling requirement in all test offices due to the internal heat gain increasing by 25kWh/m^2 . Prolonging the working hours does not change the effect of lowering the U-value on the heat gain/loss due to conduction, and hence its effect on the cooling requirement in all test offices. In addition, because the solar heat gain does not change in SC2, the effect of the g-value on the cooling demand remains the same as well.

		North					South				
	U	Q	Q _{cond}	Q _v	Q _{int}	Q _{sol}	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}
W	1.2	157	-3	-3	66	97	115	-3	-3	66	55
	2.6	154	-5	-3	66	97	112	-5	-3	66	55
M	1.2	150	9	12	66	64	158	9	12	66	72
	2.6	161	19	12	66	64	168	19	12	66	72
S	1.2	163	20	27	66	50	189	20	27	66	76
	2.6	187	44	27	66	50	213	44	27	66	76

Table 7.10 Effect of U-value on energy demand of West and South-facing offices in Abu Dhabi assuming $g = 0.5$ using steady-state calculation, SC2

		North					South				
	U	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}
W	1.2	85	-3	-3	66	25	74	-3	-3	66	14
	2.6	82	-5	-3	66	25	71	-5	-3	66	14
M	1.2	74	9	7	41	16	105	9	12	66	18
	2.6	113	19	12	66	16	115	19	12	66	18
S	1.2	126	20	27	66	13	133	20	27	66	20
	2.6	150	44	27	66	13	157	44	27	66	20

Table 7.11 Effect of U-value on energy demand of West and South-facing offices in Abu Dhabi assuming $g = 0.3$ using steady-state calculation, SC2

7.2.2 Annual results, Tas

Figure 7.13 (i, ii, iii, iv) shows the effect of the U and g-value on annual energy demand of the test offices facing North, South, East and West in Abu Dhabi, assuming the SC2 condition. It can be seen that, compared with SC1, the annual loads in the test offices increase to between 300 and 450 kWh/m². The annual energy demand remains the same: utilising the facade with a low U-value in the test offices reduces the annual energy demand irrespective of office orientation. Lowering the g-value from 0.5 to 0.3 reduces the annual energy demand of the test offices, irrespective of the U-value and orientation. The energy reduction from lowering the g-value is higher in South and West-facing offices. Annually, the test offices using the facade with $g = 0.3$ and $U = 1.2 \text{ W/m}^2\text{K}$ have the lowest annual energy demand.

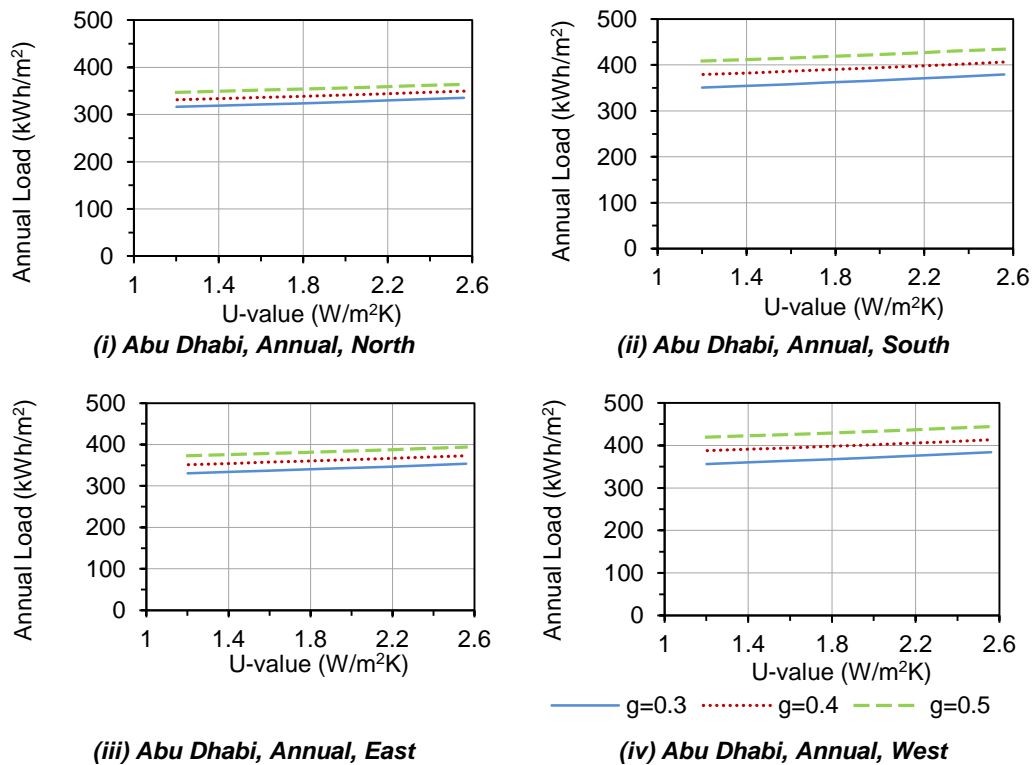


Figure 7.13 Effect of U and g-values and building orientation on annual heating/cooling load of test office using Tas, Abu Dhabi, SC2

7.2.3 Seasonal results, Tas

The seasonal total loads in the test offices facing the four orientations for winter, mid-season and summer are determined and shown in Figure 7.14 (winter), Figure 7.15 (mid-season) and Figure 7.16 (summer). The test offices have only cooling load and there is no heating requirement all year around. Generally, the seasonal cooling requirement in the test offices in SC2 is higher than that in SC1; it ranges between 70kWh/m² and 140kWh/m² in winter, in mid-season from 70kWh/m² and 120kWh/m², and in summer from 90kWh/m² to 150kWh/m². In winter, a South-facing office requires more cooling energy than the test offices facing other orientations, whereas a West-facing office has the highest cooling demand in summer.

The seasonal trends found in SC2 are the same as those found in SC1: lowering the U-value of the facades has little impact on the cooling demand in winter but it has some beneficial effect during mid-season and the effect is the most obvious in summer. In all seasons, lowering the g-value from 0.5 to 0.3 reduces the energy demand in South and West-facing offices, but the effect is less in the North and East-facing offices.

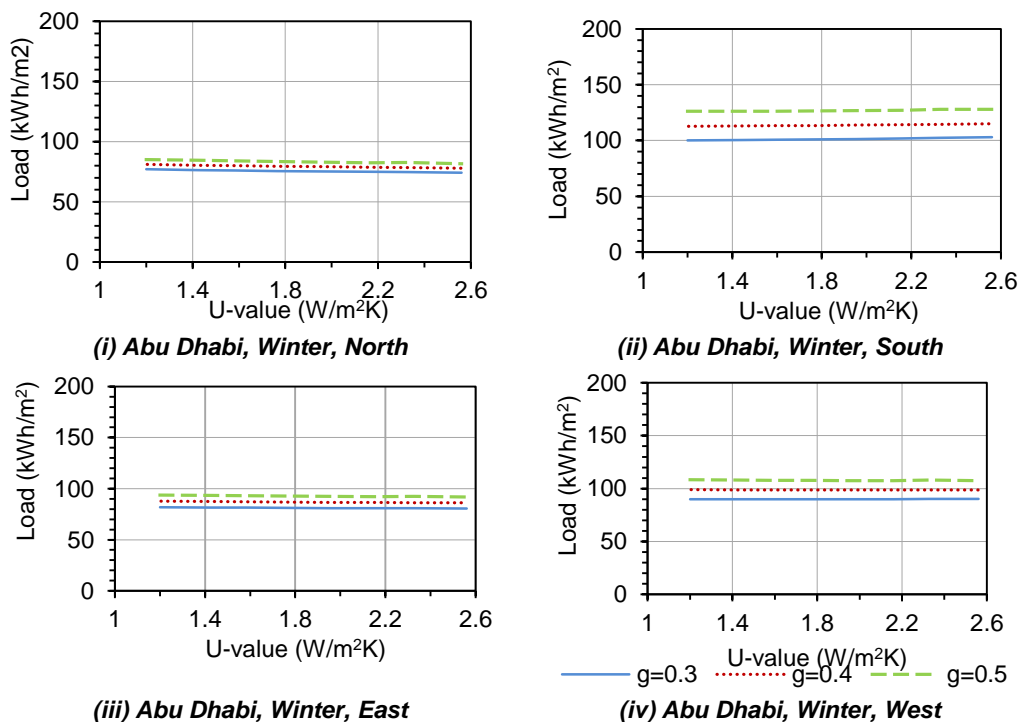


Figure 7.14 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Abu Dhabi, SC2

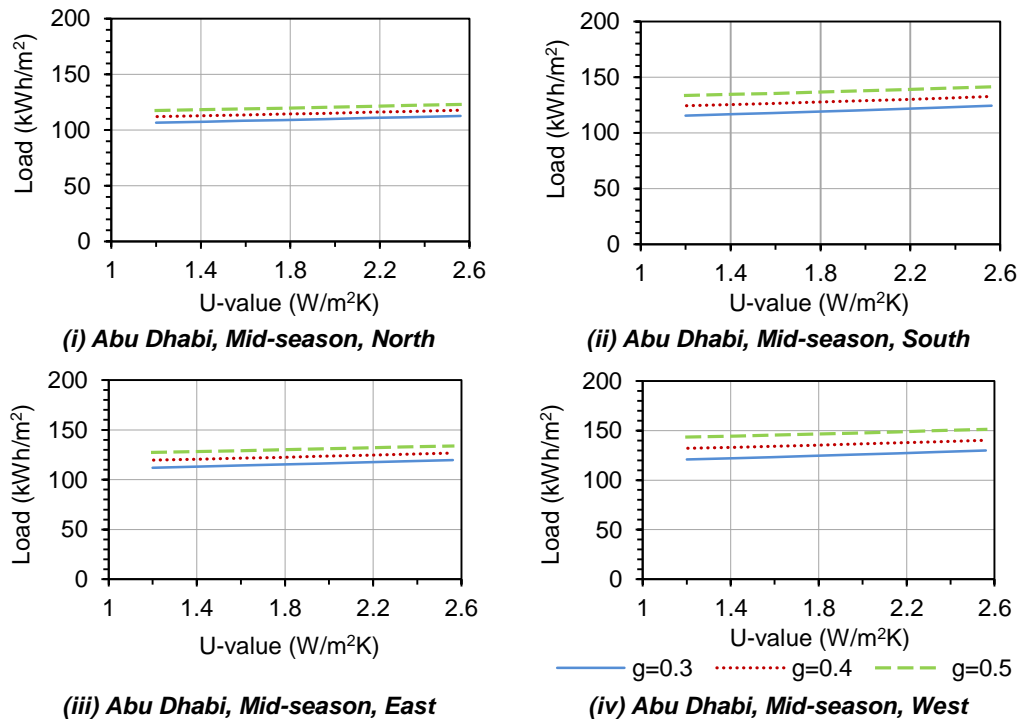


Figure 7.15 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Abu Dhabi, SC2

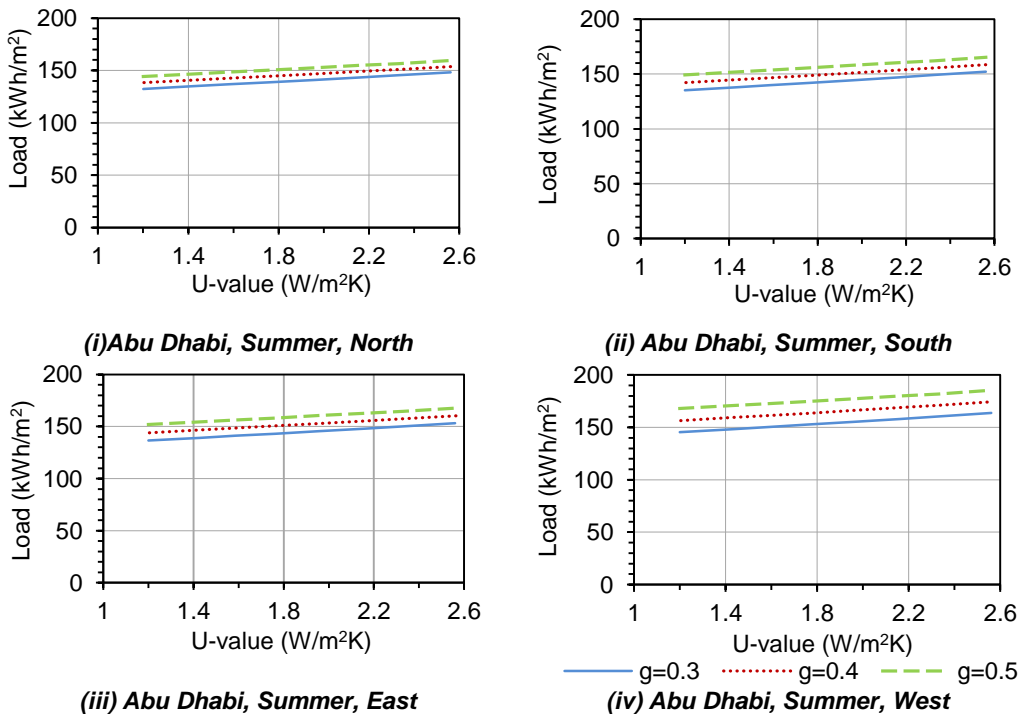


Figure 7.16 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in summer, Abu Dhabi, SC2

Breakdown of the results

Looking at the values of the principal factors by seasons shown in Table 7.12, which is for South facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and U is either $1.2 \text{ W/m}^2\text{K}$ or $2.6 \text{ W/m}^2\text{K}$, the major difference between SC1 and SC2 is that the amount of internal heat gain increases from 41 to 62 kWh/m^2 . The longer working hours also cause a greater ventilation heat gain. Therefore the total heat gains from these sources are larger and as a result cooling requirements in the test offices increase in all seasons.

Again, the effect of the U -value depends on the outdoor dry-bulb temperature, which determines the amount of conduction heat loss/gain. The patterns in SC2 and the reasons behind them are the same as in SC1. The effect of lowering a facade's U -value is most obvious in summer when the outdoor air is the hottest. Using a facade with a U -value of $1.2 \text{ W/m}^2\text{K}$ instead of $2.6 \text{ W/m}^2\text{K}$ reduces the unwanted conduction heat gain and hence the cooling requirement by 16 kWh/m^2 , whereas the value is 9 kWh/m^2 in mid-season and 1 kWh/m^2 in winter. These figures are slightly higher than those found in SC1 due to the longer operating hours.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	0	122	-10	1	62	80	-11
	2.6	0	123	-9	1	62	80	-11
M	1.2	0	132	1	16	64	53	-2
	2.6	0	141	11	16	64	53	-3
S	1.2	0	144	11	31	64	36	3
	2.6	0	160	28	31	64	36	1

Table 7.12 Effect of U -value on energy demand of South-facing offices in Abu Dhabi assuming $g = 0.5$ using T_{as} , SC2

The effect of lowering the U -value is similar in North-facing offices and the reasons behind it are also similar, apart from in winter. Table 7.13 shows that effect of lowering the U -value from 2.6 to $1.2 \text{ W/m}^2\text{K}$ on the seasonal energy demand and the principal factors in a North-facing office. Compared with the values in a South-facing office (Table 7.12), a North-facing office generally has lower cooling demand in all seasons since it receives less solar heat gain, which also is the reason for the large difference between North and South-facing offices. Note that the heat gain due to ventilation is the same.

	U	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	1.2	0	85	-8	1	65	14	13
	2.6	0	82	-13	1	65	14	15
M	1.2	0	118	1	16	66	25	9
	2.6	0	123	7	16	66	25	9
S	1.2	0	144	12	32	66	29	6
	2.6	0	159	28	32	66	29	4

Table 7.13 Effect of U-value on energy demand of North-facing offices in Abu Dhabi assuming $g = 0.5$ using Tas, SC2

Effect of g-value

Table 7.14 shows the effect of lowering the g-value of the facade from 0.5 to 0.3 on the seasonal cooling demand in South facing offices, assuming a U-value of 1.2 W/m²K. It can be seen that the cooling demand falls with a lower g-value, largely because of the decrease in solar gains. The cooling load reduction is 25 kWh/m², 18kWh/m² and 14kWh/m² in winter, mid-season and summer respectively, and these values are similar to those in SC1. Therefore, lowering the g-value from 0.5 to 0.3 can reduce the annual cooling demand by 57Wh/m², which is larger than the cooling reduction from lowering the U-value.

	g	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	0.3	0	100	-4	1	65	43	-4
	0.4	0	113	-7	1	65	62	-8
	0.5	0	126	-10	1	65	83	-12
M	0.3	0	115	5	16	66	26	2
	0.4	0	124	3	16	66	38	1
	0.5	0	133	0	16	66	51	-1
S	0.3	0	135	15	32	66	19	4
	0.4	0	142	13	32	66	28	3
	0.5	0	149	12	32	66	37	3

Table 7.14 Effect of g-value on energy demand of South-facing offices in Abu Dhabi assuming $U = 1.2$ W/m²K using Tas, SC2

Table 7.15 shows the effect of lowering the g-value of the facade from 0.5 to 0.3 on the seasonal cooling demand in North-facing offices. Lowering the facade's g-value from 0.5 to 0.3 when $U = 1.2$ W/m²K in a North-facing tested office can reduce the cooling demand in winter, mid-season and summer by 8kWh/m², 11kWh/m² and 12kWh/m² respectively, due to the decrease in the solar heat gain. The heat gain due to ventilation is the same in both North and South-facing offices whereas there is a small difference between the amounts of conduction heat gain/loss.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	0	77	-7	1	65	7	10
	0.4	0	81	-7	1	65	11	12
	0.5	0	85	-8	1	65	14	13
M	0.3	0	107	4	16	66	13	7
	0.4	0	112	2	16	66	19	8
	0.5	0	118	1	16	66	25	9
S	0.3	0	132	14	32	66	15	5
	0.4	0	138	13	32	66	22	5
	0.5	0	144	12	32	66	29	6

Table 7.15 Effect of g-value on energy demand of North-facing offices in Abu Dhabi assuming $U = 1.2 \text{ W/m}^2\text{K}$ using Tas, SC2

7.3 Effect of lowering internal gain, SC3

This section presents the Tas simulation results showing the effect of U and g-values on energy demand of Abu Dhabi offices facing North, South, East and West under the assumed SC3 condition. Here, the total internal gains are assumed to be lower at 25W/m^2 , rather than 33.7W/m^2 in SC1, and Abu Dhabi's current climate data is used.

7.3.1 Annual results, Tas

Figure 7.17 (i, ii, iii, iv) shows for North, South, East and West-facing offices in Abu Dhabi the effect of the U and g-value on the annual energy demand of the test offices. Compared with SC1, the annual loads decrease to $190\text{-}310\text{kWh/m}^2$. It can be seen that utilising a facade with a lower U-value reduces the annual energy demand in all test offices. Lowering the g-value from 0.5 to 0.3 reduces the annual energy demand of the test offices irrespective of the U-value and orientation. Again, the energy reduction from lowering the g-value is higher in South and West-facing offices. Overall, the test offices using a facade with $g = 0.3$ and $U = 1.2\text{W/m}^2\text{K}$ have the lowest annual energy demand for all orientations.

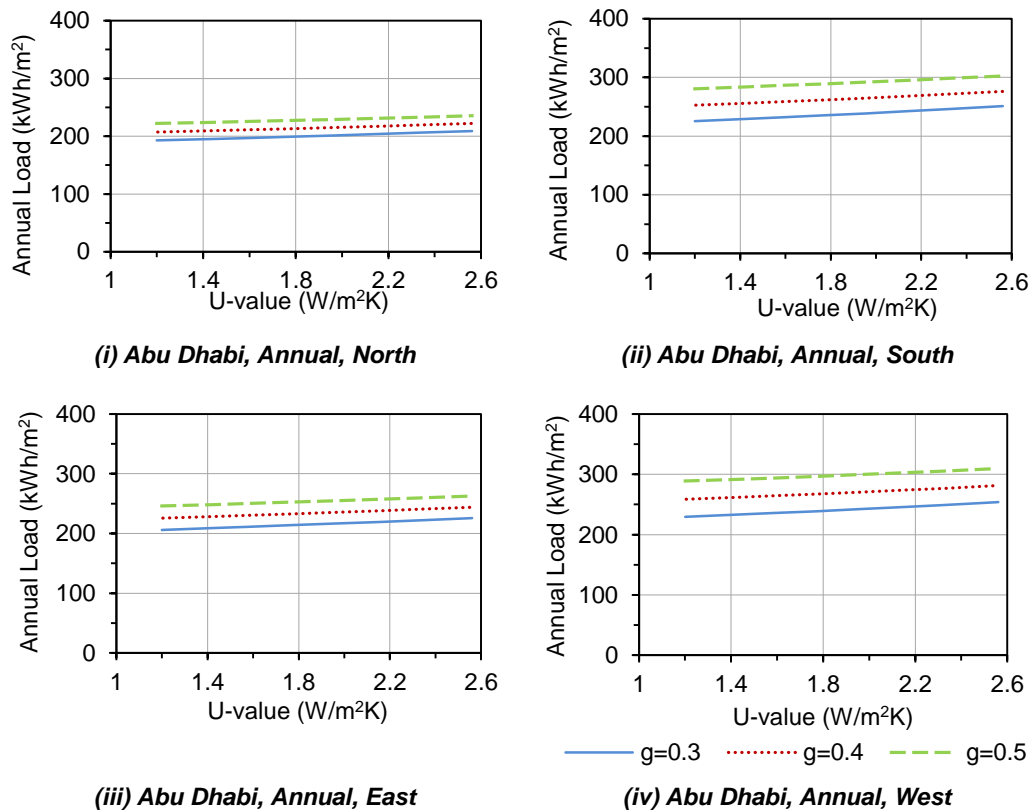


Figure 7.17 Effect of U and g-values and building orientation on annual heating/cooling load of test office using Tas, Abu Dhabi, SC3

7.3.2 Seasonal trends, Tas

The seasonal energy demand of the test offices for winter, mid-season and summer are determined and shown in Figure 7.18, Figure 7.19 and Figure 7.20, respectively. The test offices have only cooling needs and there is no heating requirement all year around. Generally, the seasonal cooling requirement in the test offices in SC3 is lower than that in SC1. It ranges between 20kWh/m² and 80kWh/m² in winter, in mid-season from 50kWh/m² to 100kWh/m², and 70kWh/m² to 120kWh/m² in summer. In winter, a South-facing office requires more cooling energy than the test offices facing in other orientations, whereas a West-facing office has the highest cooling demand in summer.

The effect of lowering the g-value on the seasonal energy demand remains the same, but the impact of lowering the U-value in SC3 is different, and smaller than found in SC1. In winter, lowering the U-value of the facades has almost no effect in South-facing offices, but it can slightly increase the cooling demand in offices facing North, East and West. Lowering the U-values has almost no effect on the cooling requirements in mid-seasons, but it can reduce the cooling demand in summer. In all seasons, lowering the g-value from 0.5 to 0.3 can reduce the energy demand in South and West-facing offices, but the effect is smaller in North and East-facing offices.

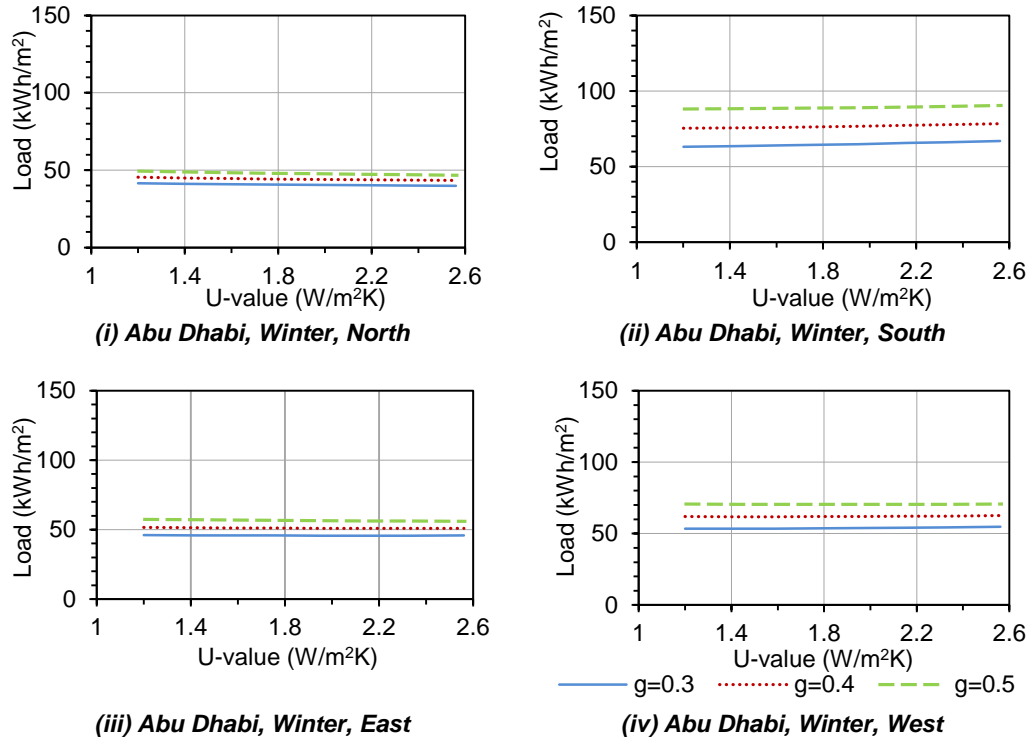


Figure 7.18 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Abu Dhabi, SC3

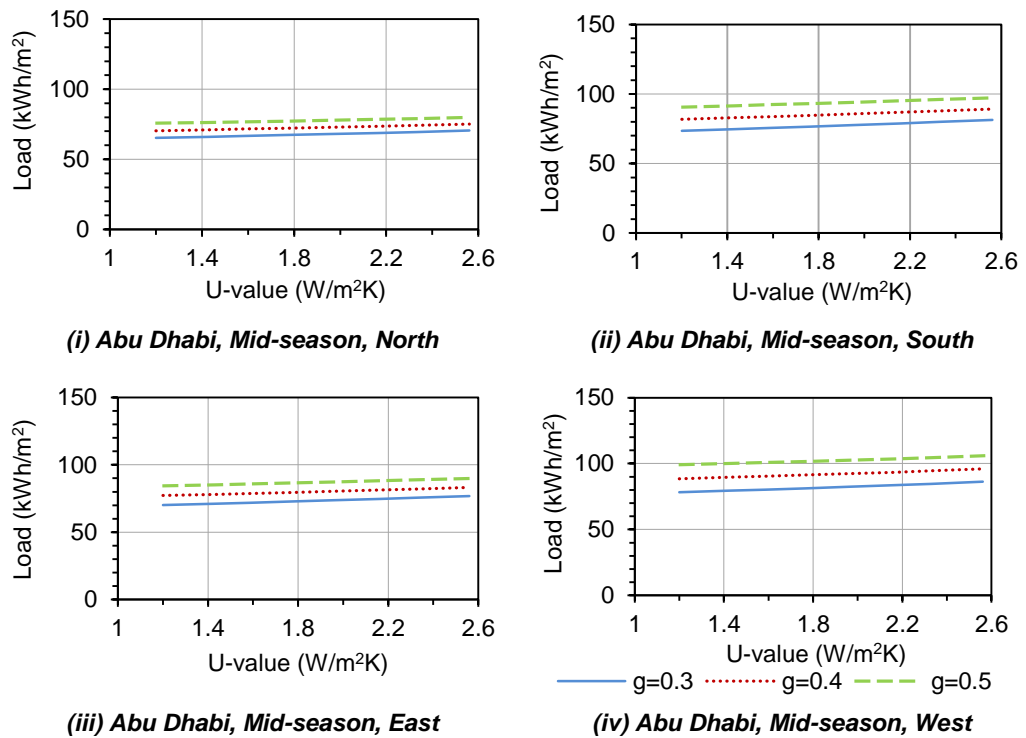
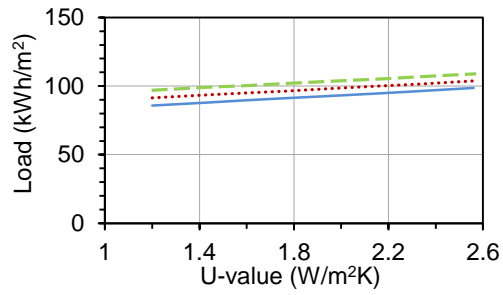
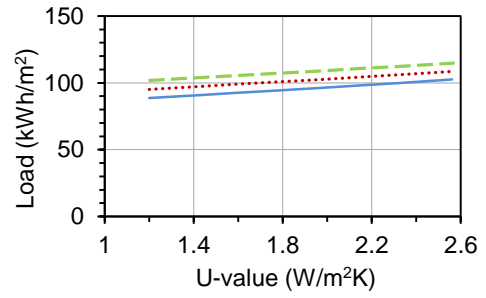


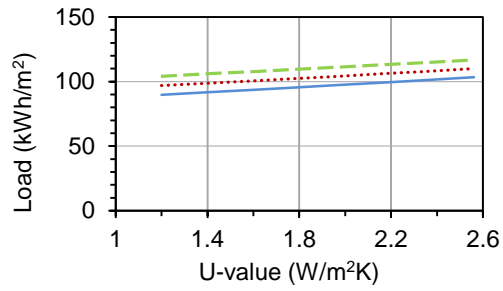
Figure 7.19 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Abu Dhabi, SC3



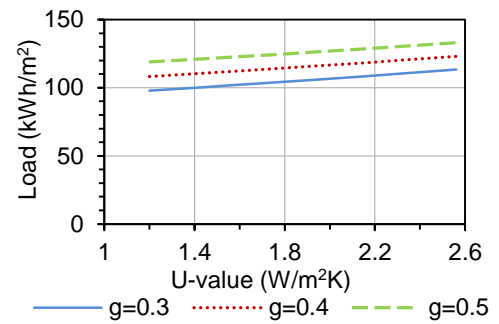
(i) Abu Dhabi, Summer, North



(ii) Abu Dhabi, Summer, South



(iii) Abu Dhabi, Summer, East



(iv) Abu Dhabi, Summer, West

Figure 7.20 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in summer, Abu Dhabi, SC3

Breakdown of the results

Further insights are obtained by considering the values of the principal factors influencing the energy demand. Table 7.16 shows the results for South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and U is either $1.2 \text{ W/m}^2\text{K}$ or $2.6 \text{ W/m}^2\text{K}$. The values in the table are the summations of hourly energy demand for these seasons. The major difference between SC1 and SC3 is that the internal heat gain decreases from 41 to 28 kWh/m^2 .

Again the effect of the U -value depends on the outdoor dry-bulb temperature, which determines the amount of conduction heat loss/gain. The results in SC3 and the reasons behind them are the same as in SC1. The effect of lowering facade's U -value is largest in summer when the outdoor air is the hottest; it reduces the unwanted conduction heat gain and hence the cooling requirement by 9 kWh/m^2 . In mid-season, when the temperature difference is smaller, lowering the U -value reduces the cooling demand by 4 kWh/m^2 , and by 1 kWh/m^2 in winter. These values are slightly lower than those found in SC1.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	0	88	-11	3	29	83	-15
	2.6	0	90	-9	3	29	83	-15
M	1.2	0	91	-1	15	29	51	-3
	2.6	0	97	6	15	29	51	-4
S	1.2	0	102	9	26	29	37	0
	2.6	0	115	23	26	29	37	-1

Table 7.16 Effect of U -value on energy demand of South-facing offices in Abu Dhabi assuming $g = 0.5$ using T_{as} , SC3

The influence of lowering the U -value is similar in North-facing offices, and the reasons behind them are also similar, apart from in winter. Table 7.17 shows the effect of lowering the U -value from 2.6 to $1.2 \text{ W/m}^2\text{K}$ on seasonal energy demand and the principal factors in a North-facing office. Compared with the values in a South-facing office (Table 7.16), a North-facing office generally has lower cooling demand in all seasons because it receives less solar heat gain, which also is the reason for the large difference between North and South-facing offices.

	U	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	1.2	0	49	-9	3	29	14	12
	2.6	0	47	-13	3	29	14	14
M	1.2	0	76	0	15	29	25	6
	2.6	0	80	4	15	29	25	7
S	1.2	0	97	9	26	29	29	3
	2.6	0	109	22	26	29	29	2

Table 7.17 Effect of U-value on energy demand of South-facing offices in Abu Dhabi assuming $g = 0.5$ using Tas, SC3

Effect of g-value

Table 7.18 shows the effect of lowering the g-value of the facade from 0.5 to 0.3 on the seasonal cooling demand in South facing offices, assuming a U-value of 1.2 W/m²K in SC3. It can be seen that the cooling demand falls with a reducing g-value, largely because of the decrease in solar gains. The cooling load reduction is 25kWh/m², 18kWh/m² and 14kWh/m² in winter, mid-season and summer respectively, and these values are similar to those in SC1. Therefore lowering the g-value from 0.5 to 0.3 can reduce the annual cooling demand by 57Wh/m², which is larger than the amount of cooling reduction from lowering the U-value.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	0	63	-4	3	29	43	-7
	0.4	0	75	-8	3	29	62	-11
	0.5	0	88	-11	3	29	83	-15
M	0.3	0	74	4	15	29	26	0
	0.4	0	82	1	15	29	38	-2
	0.5	0	91	-1	15	29	51	-3
S	0.3	0	89	13	26	29	19	1
	0.4	0	95	11	26	29	28	1
	0.5	0	102	9	26	29	37	0

Table 7.18 Effect of g-value on energy demand of South facing offices in Abu Dhabi assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC3

Table 7.19 shows the effect of lowering the g-value of the facade from 0.5 to 0.3 on seasonal cooling demand in North-facing offices. Lowering the facade's g-value from 0.5 to 0.3, when $U = 1.2\text{W/m}^2\text{K}$, in a North-facing tested office can reduce the cooling demand in winter, mid-season and summer by 8kWh/m², 11kWh/m² and 12kWh/m² respectively, due to the decrease in the solar heat gain. The heat gain due to ventilation is the same in both North and South-facing offices, whereas there is a small difference in the conduction heat gain/loss.

	g	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
W	0.3	0	41	-6	3	29	7	9
	0.4	0	45	-8	3	29	11	10
	0.5	0	49	-9	3	29	14	12
M	0.3	0	65	3	15	29	13	5
	0.4	0	70	1	15	29	19	6
	0.5	0	76	0	15	29	25	6
S	0.3	0	86	12	26	29	15	3
	0.4	0	91	11	26	29	22	3
	0.5	0	97	9	26	29	29	3

Table 7.19 Effect of g-value on energy demand of North-facing offices in Abu Dhabi assuming $U = 1.2 \text{ W/m}^2\text{K}$ using Tas, SC3

7.4 Effect of climate change, SC4

This section investigates the effect of climate change on the energy performance of high-performance facades in offices in Abu Dhabi. The future climate file, which is the 2050 medium emission scenario, is used. The standard working scenario is assumed here: 10 working hours per day, 7 days a week, with assumed internal gains of 33.7 W/m² in tested offices. Test results from Tas simulations for Abu Dhabi under a climate change scenario are presented and discussed.

Abu Dhabi future climate data, 2050

Table 7.20 shows the seasonal average values of climate data used in Tas simulations in 2050. The indoor design temperature has been set as 22°C. Compared with Abu Dhabi's current scenario, the seasonal average temperature increases by 2.5°C, 2.7°C and 0.9°C in winter, mid-season and summer, respectively. The solar irradiation decreases by 232kWh/m², 101 kWh/m², 421kWh/m² in winter, mid-season and summer respectively. Winter is the least warm time of the year, with the lowest solar irradiance; summer is hottest, with the greatest solar irradiance.

	$T_{\max} (^{\circ}\text{C})$	$T_{\min} (^{\circ}\text{C})$	$T_{\text{av}} (^{\circ}\text{C})$	$S \text{ (kWh/m}^2\text{)}$
Winter	33.0	13.8	23.1	6,830
Mid-season	40.7	20.5	29.7	7,969
Summer	47.0	28.4	34.3	8,528

Table 7.20 Seasonal average temperature and solar radiation data for Abu Dhabi, 2050

7.4.1 Annual results

Figure 7.21 (i, ii, iii, iv) shows for North, South, East and West-facing offices in Abu Dhabi the effect of the U and g-value on annual energy demand of the test offices using the climate file of Abu Dhabi in 2050 (SC4). Compared with SC1, the annual loads in the test offices increase to between 250 and 400kWh/m². The trends found in the annual load results are the same: utilising the facade with a lower U-value can reduce the annual energy demand in all test offices. Lowering the g-value from 0.5 to 0.3 can reduce the annual energy demand of the test offices, irrespective of the U-value and orientation. Again, the amount of energy reduction from lowering the g-value is higher in South and West-facing offices. Overall, it can be seen that the test offices using a lower g-value (0.3) and lower U-value facade have the lowest annual energy demand for all orientations.

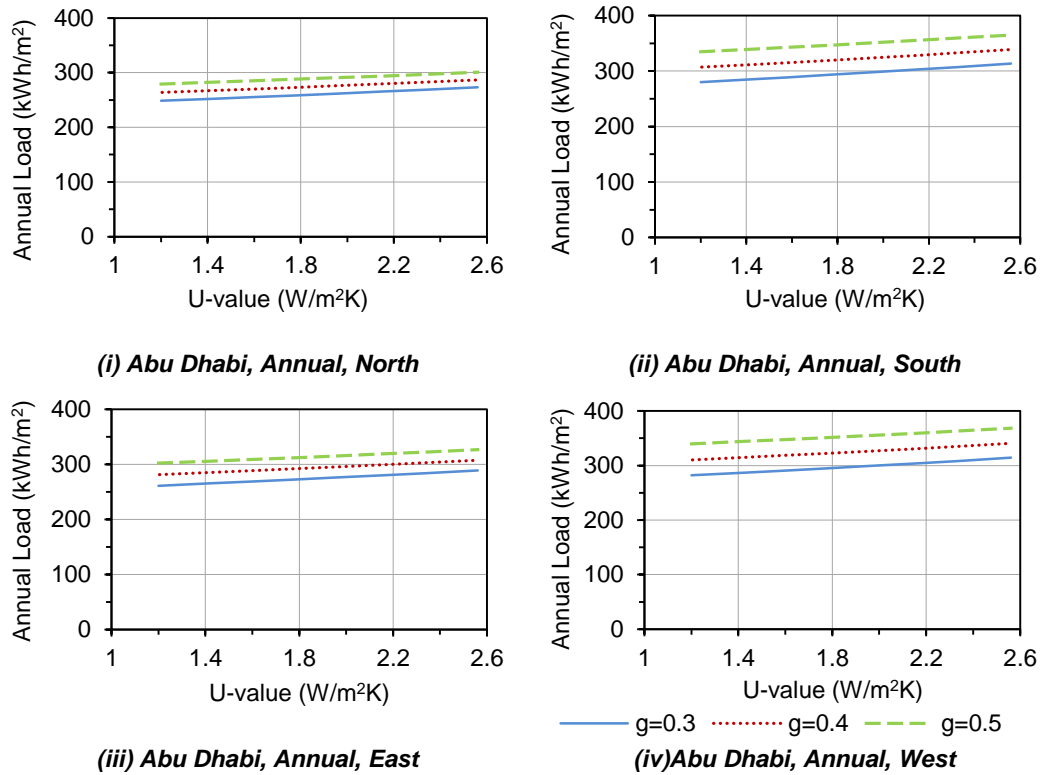


Figure 7.21 Effect of U and g-values and building orientation on annual heating/cooling load of test office under Tas, Abu Dhabi, SC4

7.4.2 Seasonal performance, Tas

Similarly, the energy demand by season is determined and is shown in Figure 7.22 (winter), Figure 7.23 (mid-season) and Figure 7.24 (summer). The cooling requirement in winter is lowest, from 50kWh/m^2 to 110kWh/m^2 , in mid-season the range is 80kWh/m^2 to 130kWh/m^2 , and 100kWh/m^2 to 150kWh/m^2 in summer, all of which are slightly higher than the seasonal load found in SC1. These increases in seasonal cooling loads are understandable because of the general rise in the outdoor dry-bulb temperature in the climate change scenario. In winter, a South-facing office requires more cooling energy than the test offices facing in other orientations, whereas a West-facing office has the highest cooling demand in summer.

The effect of lowering the U-value and g-value of the facade on the seasonal cooling requirements of the test offices remains the same. Lowering the U-value has little effect on the cooling demand in winter, but it can reduce the office cooling loads by a small amount in mid-season and the benefit is the most obvious in summer. In all seasons, lowering the g-value from 0.5 to 0.3 can reduce the energy demand in South and West-facing offices, but the effect is smaller in the test offices facing North and East.

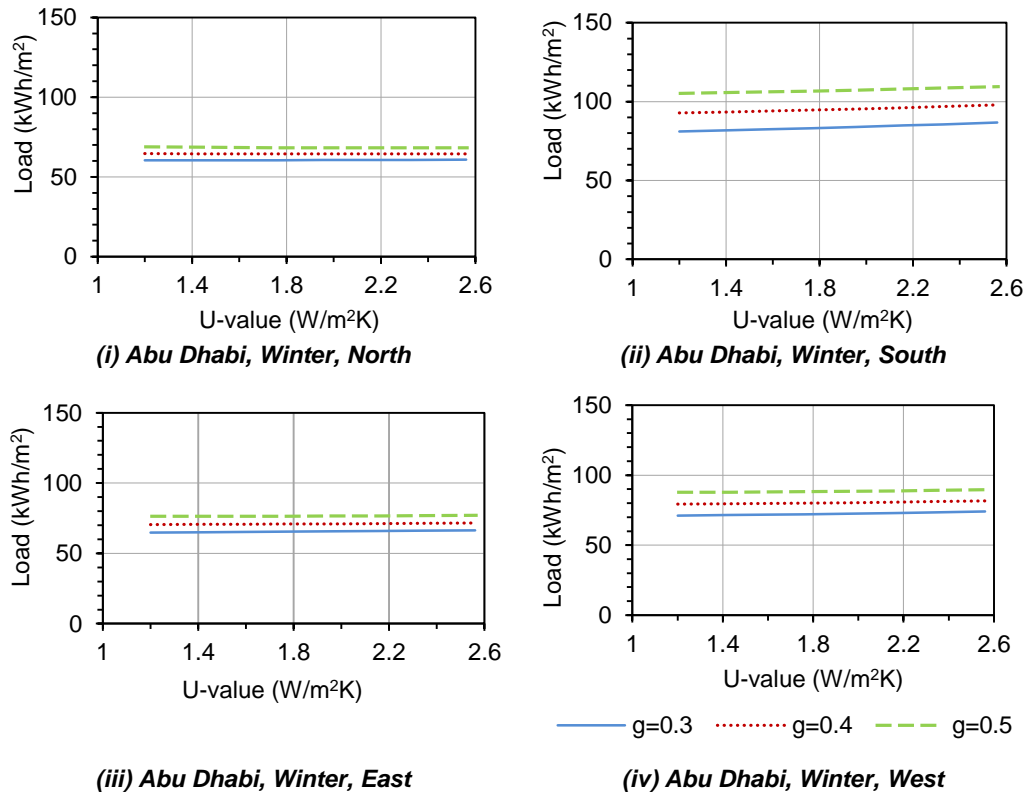


Figure 7.22 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in winter, Abu Dhabi, SC4

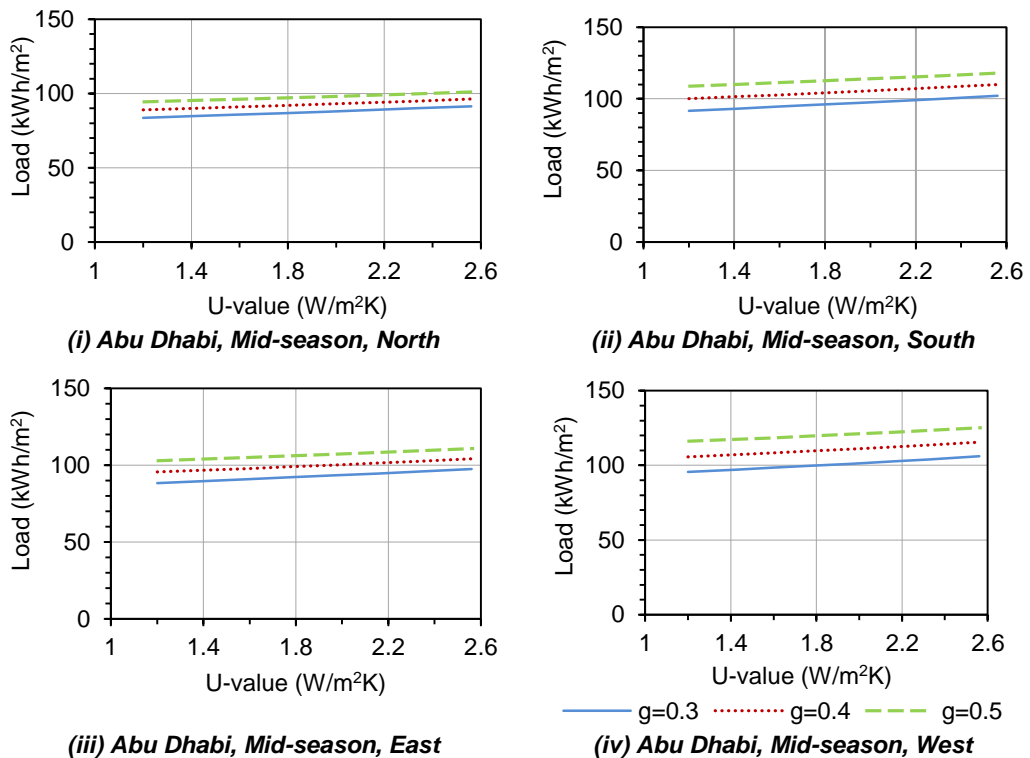


Figure 7.23 Effect of U and g-values and building orientation on heating/cooling load of test office using Tas in mid-season, Abu Dhabi, SC4

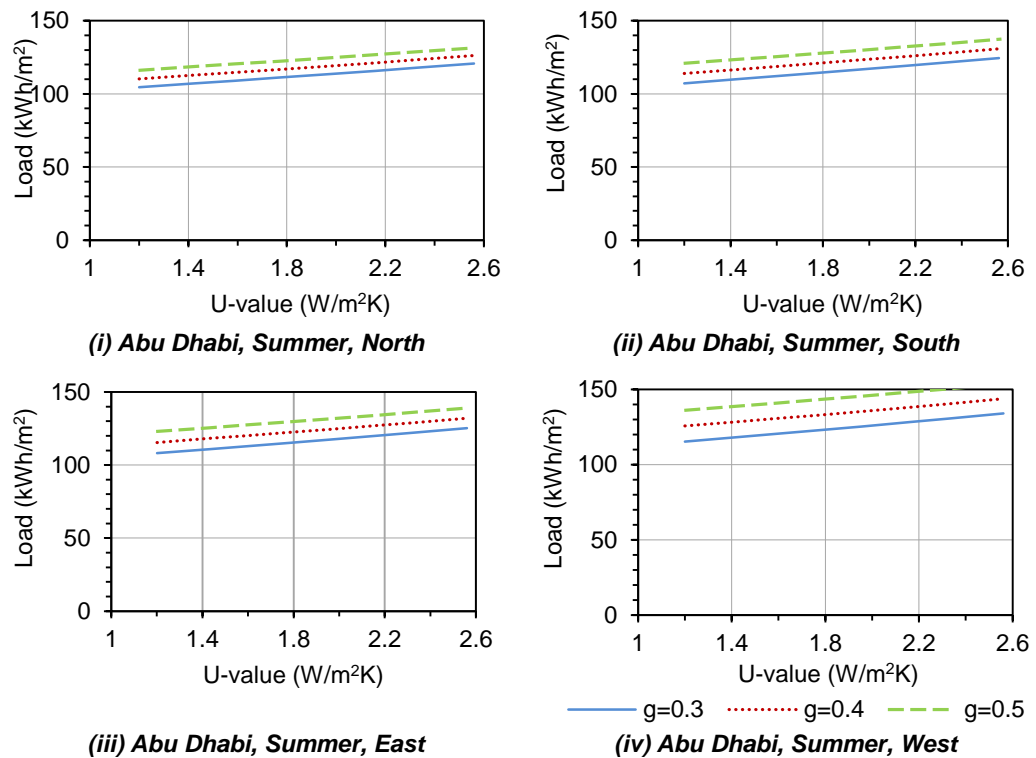


Figure 7.24 Effect of U and g-values and building orientation on heating/cooling load of test office under Tas in summer, Abu Dhabi, SC4

Breakdown of the results

Looking at the values of the principal factors by seasons shown in Figure 7.21, which is for South-facing offices in winter (W), mid-season (M) and summer (S), assuming $g = 0.5$ and U either $1.2 \text{ W/m}^2\text{K}$ or $2.6 \text{ W/m}^2\text{K}$, compared with SC1, the conduction heat loss in winter is smaller and the heat gains due to conduction in mid-season and summer are higher, due to the increased outdoor temperatures in the future climate scenario. However, the change in the solar heat gain is small. The effect of lowering the U-value stays the same: in winter, lowering U-value has little effect on conduction heat loss because the outdoor temperature is close to the indoor design temperature. During mid-season, the outdoor air is hotter than the indoor design temperature, and lowering U-value of the facade limits the unwanted conduction heat gains. The effect is most obvious in summer, when the outdoor temperature is the highest of the year and well above the indoor design temperature.

	U	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	1.2	0	105	-8	6	40	80	-13
	2.6	0	110	-4	6	40	80	-13
M	1.2	0	109	2	17	41	51	-3
	2.6	0	118	12	17	41	51	-3
S	1.2	0	121	14	27	41	39	0
	2.6	0	137	32	27	41	39	-2

Table 7.21 Effect of U-value on energy demand of South-facing offices in Abu Dhabi assuming g = 0.5 using Tas, SC4

Table 7.22 shows the effect of lowering the U-value from 2.6 to 1.2 W/m²K on seasonal energy demand and the principal factors in a North-facing office. In North-facing offices where there is a lower solar heat gain, the cooling demand is lower. The influence of lowering the U-value is the same in mid-season and summer in North-facing offices, and for the same reasons. The results in winter are slightly different from in South-facing offices, but the difference is not large.

	U	Q _h	Q _c	Q _{cond}	Q _{air}	Q _{int}	Q _{sol}	Q _b
W	1.2	0	69	-6	6	40	16	12
	2.6	0	68	-8	6	40	16	13
M	1.2	0	94	3	17	41	26	7
	2.6	0	101	10	17	41	26	6
S	1.2	0	116	14	27	41	31	3
	2.6	0	132	31	27	41	31	1

Table 7.22 Effect of U-value on energy demand of North-facing offices in Abu Dhabi assuming g = 0.5 using Tas, SC4

Effect of g-value

Table 7.23 shows the effect of lowering the g-value of the facade from 0.5 to 0.3 on the seasonal cooling demand in South-facing offices, assuming that the U-value is 1.2 W/m²K. It can be seen that the cooling demand falls by reducing the g-value, largely because of the decrease in solar gains. The cooling load reduction is 24kWh/m², 17kWh/m² and 14kWh/m² in winter, mid-season and summer respectively, hence 55Wh/m² annually, and these values are similar to those in SC1. Therefore, the decrease in solar irradiance due to climate change is small and does not significantly alter the influence of lowering the g-value on the cooling demand of offices in Abu Dhabi.

		Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	0.3	0	81	-1	6	40	41	-5
	0.4	0	93	-5	6	40	60	-9
	0.5	0	105	-8	6	40	80	-13
Mid-season	0.3	0	92	7	17	41	26	1
	0.4	0	100	5	17	41	38	-1
	0.5	0	109	2	17	41	51	-3
Summer	0.3	0	107	17	27	41	20	2
	0.4	0	114	16	27	41	29	1
	0.5	0	121	14	27	41	39	0

Table 7.23 Effect of g-value on energy demand of South-facing offices in Abu Dhabi assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC4

Table 7.24 shows the effect of lowering the g-value of the facade from 0.5 to 0.3 on the seasonal cooling demand in North-facing offices. Lowering the facade's g-value from 0.5 to 0.3 when $U = 1.2\text{W/m}^2\text{K}$ in a North-facing tested office can reduce the cooling demand in winter, mid-season and summer by 8kWh/m^2 , 10kWh/m^2 and 12kWh/m^2 respectively, due to the decrease in the solar heat gain. The heat gain due to ventilation is the same in both North and South-facing offices, whereas there is a small difference in the conduction heat gain/loss.

		Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	0.3	0	61	-4	6	40	9	9
	0.4	0	65	-5	6	40	12	10
	0.5	0	69	-6	6	40	16	12
Mid-season	0.3	0	84	6	17	41	14	6
	0.4	0	89	5	17	41	20	6
	0.5	0	94	3	17	41	26	7
Summer	0.3	0	104	17	27	41	16	3
	0.4	0	110	15	27	41	24	3
	0.5	0	116	14	27	41	31	3

Table 7.24 Effect of g-value on energy demand of North-facing offices in Abu Dhabi assuming $U = 1.2\text{W/m}^2\text{K}$ using Tas, SC4

7.5 Results summary and conclusions

The effect of a facade's U-value and g-value has been assessed in tested offices facing North, East, West and South under four scenarios. SC1 is the normal working scenario, SC2 is prolonged working hours, SC3 analyses a lower internal gain and SC4 climate change. Table 7.25 presents the numerical results used to produce the annual energy demand figures for the four tested scenarios, which describe the present design

conditions and the potential uncertainties. The effect of lowering the U-value from $2.6\text{W/m}^2\text{K}$ to $1.2\text{W/m}^2\text{K}$ is also calculated and included in the table.

It can be concluded from this study that using low U and low g-value facades can reduce the annual cooling requirements in offices in Abu Dhabi.

It can be seen in Table 7.25 that in the normal office working schedule (SC1), utilising lower U-value facades can reduce the annual energy demand by 12 to 24kWh/m^2 in the test offices. When the g-value is 0.3, lowering the U-value reduces the annual energy demand by 15 to 24kWh/m^2 , and by 14 to 22kWh/m^2 in the cases where the g-value is 0.4, and by 12 to 20kWh/m^2 when the g-value is 0.5.

Even facing uncertainties such as variations in internal heat gains (SC2 and SC3) and climate change (SC4), lowering the U-value of the facade from 2.6 to $1.2\text{W/m}^2\text{K}$ can always reduce the annual energy demand of the tested offices facing North, East, South and West. However, the energy reduction achieved by reducing the U and g-values of the facades is different in each scenario. In all tested scenarios, the effect of lowering the U-value is greater when the facade's g-value is lower, i.e. when $g=0.3$.

The effect of lowering the g-value is generally the same in all test scenarios. For example, in a North-facing office: lowering the g-value from 0.5 to 0.4 can reduce the annual energy demand by around 23kWh/m^2 , whereas lowering the g-value from 0.4 to 0.3 can reduce the annual energy demand by 15kWh/m^2 in SC1-4. The effect of lowering the U-value and g-value is more obvious in the North facing-office, where the solar heat gain is lower than in the other orientations. Overall, energy demand is least when utilising a lower U-value coupled with a lower g-value facade in offices in Abu Dhabi, irrespective of orientation.

		SC1				SC2				SC3				SC4			
	U	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
g=0.3	1.20	223	237	256	260	316	330	351	356	193	206	225	229	249	261	280	282
	1.43	226	240	260	264	319	334	355	360	195	209	229	233	252	266	285	287
	1.59	227	242	263	266	321	337	358	363	197	211	232	236	255	269	289	291
	1.77	229	244	266	269	324	339	362	367	199	214	235	239	258	272	293	295
	1.96	231	247	269	273	326	343	366	371	201	217	239	242	262	276	298	299
	2.16	234	250	273	276	329	346	370	375	204	220	243	246	265	280	303	304
	2.33	236	252	276	279	332	349	374	379	206	222	246	249	269	284	307	308
	2.56	239	256	281	284	335	354	379	384	209	226	251	254	273	289	313	314
	2.6-1.2	15	19	25	24	19	23	29	28	16	20	26	25	24	28	34	32
g=0.4	1.20	238	257	283	290	332	351	379	388	207	226	252	259	264	282	307	311
	1.43	240	259	287	293	334	355	383	391	209	228	256	262	267	286	312	315
	1.59	241	261	289	295	336	357	386	394	211	230	259	264	270	289	315	318
	1.77	243	263	292	298	338	360	390	397	213	233	261	267	273	292	319	322
	1.96	245	266	295	301	341	363	393	401	215	235	265	270	276	295	324	326
	2.16	247	268	299	304	344	366	398	405	217	238	269	274	280	299	329	331
	2.33	249	271	302	307	346	369	401	408	219	241	272	277	283	303	333	335
	2.56	252	274	306	311	350	373	406	414	222	244	276	281	287	308	339	341
	2.6-1.2	14	17	23	22	18	22	27	26	15	18	24	23	23	26	32	30
g=0.5	1.20	253	277	312	320	347	373	409	420	222	246	281	289	279	302	335	340
	1.43	255	279	315	323	350	376	413	423	224	248	284	292	283	306	339	344
	1.59	256	281	317	325	351	378	415	426	225	250	286	294	285	309	343	347
	1.77	257	283	320	327	354	381	419	429	227	252	289	296	288	312	347	351
	1.96	259	285	322	330	356	384	422	432	229	255	292	299	291	315	351	355
	2.16	261	287	326	333	359	387	426	436	231	257	295	303	294	319	355	359
	2.33	263	290	329	336	361	390	430	440	233	259	298	305	297	322	359	363
	2.56	265	293	333	340	364	393	434	444	236	263	303	310	301	327	365	368
	2.6-1.2	12	16	21	20	17	20	26	24	13	17	22	21	22	25	30	28

Table 7.25 Effect of U-value and g-value on annual cooling load, Abu Dhabi, Tas

7.5.2 Conclusions

1. In Abu Dhabi, the outdoor temperature is hot. In winter, the outdoor temperature is a couple of degrees lower than the indoor temperature, but outdoors is significantly higher than indoors throughout the rest of the year. The combined effect of the high outdoor temperature and high solar irradiance and internal heat gains is that there is high cooling demand all year around.
2. Lowering the U-value of the facade reduces the heat infiltration and hence the cooling demand in the summer when outdoors is hottest during the year; the effect is less in mid-season and very little in winter.
3. Utilising facades with a low g-value reduces the solar heat gain and the annual cooling demand all year around.
4. South facing facades receive the most amount of solar irradiation in winter and the least amount in summer which is opposite to the North facing facade.
5. Therefore, it is better to use a facade with low U and low g-value facades in offices in Abu Dhabi.
6. In general, longer working hours increase energy usage for cooling, but the effect of lowering the U-value and g-value of the facades remains the same.
7. Lower internal gains under normal working hours (SC3) decrease the office cooling requirement because of the reduction in the internal heat gain. Again, it is better to use low U and g-value facades.
8. Climate change causes an increase in the outdoor temperature and hence an increase in the annual cooling requirement by around 10%. The effect of lowering the U and g-value of the facade on seasonal energy demand remains the same.
9. In Abu Dhabi, the outdoor temperature also affects the cooling demand in terms of the heat gain or loss due to conduction and ventilation; however, its effect is less than the changes in the solar heat gains in different seasons. The amount of cooling needed in the test offices is lowest in winter and highest in summer, irrespective of orientation.

CHAPTER 8 STRATEGIES FOR LOW ENERGY AND LOW CARBON OFFICES AND PROPOSED CHANGES TO THE UK'S BUILDING REGULATIONS

The aim of this project is primarily to investigate the influence of high performance facades on energy demand and CO₂ emissions of office buildings in Caribou, London, Hong Kong and Abu Dhabi. London has cold winters and mild summers whereas Hong Kong is always warm and humid, both cities have high office density. Caribou has a cold climate and Abu Dhabi's is classified as 'hot and arid'. Furthermore, in order to create 'future proof' designs, the effect of uncertainties, i.e. extended working hours, lower internal gains and climate change, on facade designs are also studied. Chapter 4 to 7 present the results showing the influence of high performance facades on energy demand of offices in these four locations, under varied internal and climate conditions.

The common assumption is that the lower the buildings' energy demand, the lower the CO₂ emissions. This chapter compares the energy demand and CO₂ emissions of offices in these four locations. Based on the results, low energy and low carbon office design strategies and improvements to the Building Regulations in the UK are proposed. We begin by reviewing the energy demand results obtained in Chapter 4 to 7.

8.1 Reducing energy demand

8.1.1 Energy demand results summary

The effect of lowering the U-values and g-values of office facades are different in different climates. The energy demand results from SC1 for the offices in the four studied locations are compared here.

It is well established that the lower the U-value of a wall the lower the annual energy demand due to heating and cooling. However, authors such as Masoso and Grobler (2008) pointed out that there is a point of inflection of U-value below which it increases the energy demand in both hot and cold climates. The results from this study further clarifies the influence of low U-value facades in office buildings under different climates..

In London, it can be seen in Chapter 4 that utilizing low U-value facades increases annual energy demand in offices irrespective of orientation. These results challenge the conventional understanding of the benefits of good insulation in London. London is

thought to be a heating dominating place and hence better insulation is desirable. It can be seen that this is not true in office buildings where internal heat gains are high.

Although both Hong Kong and Abu Dhabi offices only have cooling requirements all year around, the effect of lowering facades' U-value is different. In Hong Kong where the climate is sub-tropical, the results in Chapter 5 suggest that lowering the U-value has a marginal effect on annual energy demand. In Abu Dhabi, energy demand reduction of around 6% can be observed in all cases when lower U-value facade is used. Therefore, low U-value facade is only effective in extreme hot place because it can reduce a large amount of heat infiltration.

The influence of lower U-value facade in offices in cold climate found in this study conforms with the conventional understanding. The use of facades with low U-values reduces the annual energy demand in Caribou and the trend is true for most cases apart from for the South facing office when facade's g-value is 0.5. However, the annual cooling demand is high when a low U-value facade is used.

It is surprising to find that the use of low g-value facades in Caribou where the climate is cold reduces annual energy demand. Because it has a cold climate, it has been recommended in the literature that a high g-value should be used in offices in such climate. However, due to the high cooling demand in summer, lower g-value facades perform better overall.

Seasonal results explains the reasons

The reason behind these differences can be explained by looking at the seasonal trends of each locations which are included in results presented in Chapter 4-7.

After reviewing the seasonal trends in each location, it is found that the benefit of U-value largely depends on the temperature difference between indoor and outdoor and the solar irradiance level. In London, for example, although the average outdoor temperatures are lower than indoor design values all year round, a small amount of heating would only appear to be necessary during winter because of high heat gains from solar irradiation and occupancy values at other times of the year. There can be cooling requirements in winter, for example, in South orientation where the solar irradiation is higher than the rest of the orientations. During most of the time of a year, particularly in summer, the use of facades with low U-values and high g-values will trap heat inside the building and increase energy usage because of the higher demand for

cooling. Therefore, it is not surprising that in London there is an overall increase in energy demand with decreasing U-value and increasing g-value.

In Hong Kong, although there is only a cooling requirement at all times of the year, the influence of high performance facades is different in different seasons due to the difference in temperature difference between indoor and outdoor. In winter, despite the fact that the outdoor temperature is cooler than indoors, there is nevertheless a cooling demand because of relatively high solar irradiation levels. This scenario is similar to London in summer. However, during mid-season and summer, the average outdoor temperature is higher than the indoor design temperature but the difference is not large. Good insulation stops unwanted conductive heat gains into the indoor controlled cool environment during mid-season and summer. A change in U-value has little impact on annual load. Moreover, it is worth noting that despite the smaller differences between indoor and outdoor temperatures, more energy is required to regulate temperatures in office buildings in Hong Kong compared with London.

Caribou has the coldest climate of the four locations considered. In winter, the amount of heat loss due to conduction and ventilation is high because the outdoor air temperature is much cooler than the indoor design temperature. Using lower U-value facades reduces a large portion of the heating demand in winter. Generally the colder climate means that there is less cooling load during mid-season months. However in summer, there are still cooling needs for offices facing all orientations. Overall, lower U-value facade is beneficial especially when the g-value is also low (0.3).

Abu Dhabi has a hotter climate than Hong Kong. The outdoor temperature is much higher than the indoor temperature during most of the year. It can be observed that lower U-value facades can reduce cooling load during both mid-season and summer months because they stop heat infiltration. Hence, annually, using low U-value facade is beneficial.

Table 8.1 summarises the energy performance of low U-value facade in each season and annually for these four locations.

SC1: Effect of lowering U-value from 2.6 to 1.2 W/m ² K		
	The effect of lowering U-value	Climate data
Caribou Annual	good apart from when g=0.5, South orientation	T_{av} = 11.75, S= 5290
W	heating demand only, lower U-value facade reduces heating demand by a large amount	T _{av} = -7.65, S = 3285
M	a mix of heating and cooling load, lower U-value facade performs worse in some cases	T _{av} = 3.9, S = 5804
S	cooling load only, lower U-value facade increases cooling load	T _{av} = 15.5, S = 6781
London Annual	Worse	T_{av} = 11.4, S=3549
W	there is a mix of heating and cooling load, 'point of inflexion' exists	T _{av} = 6.8 S = 1468
M	cooling demand only, lower U-facade requires more cooling load.	T _{av} = 10.5, S = 3780
S	cooling demand only, lower U-facade requires more cooling load.	T _{av} = 16.8, S = 5401
HK Annual	marginal	T_{av} = 23, S=4211
W	cooling demand only, lower U-value facade increases cooling demand	T _{av} = 17.7 S = 3769
M	cooling demand only, trend lines are almost flat	T _{av} = 23.2 S = 4008
S	cooling demand only, lower U-value facade reduces cooling load.	T _{av} = 28.2 S = 4856
Abu Dhabi Annual	Good	T_{av} = 26, S=8027
W	Marginal effect, lower U-value facade is slightly worse in some cases	T _{av} = 20 S = 7062
M	trend lines are almost flat, lower U-value facade are slightly better	T _{av} = 27 S = 8070
S	lower U-value facade reduces cooling demand	T _{av} = 33.2 S = 8949

Table 8.1 Results comparison of four test locations, TAS

The effect of extended working hours

In all locations, extending the working hours from 10 hours to 16 hours per day does not change the effect of lowering the U-value on the annual energy demand. The extended working hours occur either in early morning or late evening when there is little solar radiation. In London and Caribou, both the heating and cooling loads increase due to the extended working hours but the increase in cooling load is larger. Understandably, in both Hong Kong and Abu Dhabi offices, the annual cooling demands increase. Generally, the annual energy demands increase in all offices due to the longer building's operative hours.

The effect of climate change

With the global concern of climate change, it is necessary to study its effect on the selection of facades. In Caribou and London, climate change reduces the heating needs in winter but increases the annual cooling demand. Overall, it is still beneficial to use lower U-value facades and the annual energy demand increases due to the climate change. Climate change increases the cooling energy demand and in turn the annual energy demand in Hong Kong and Abu Dhabi.

The effect of lowering internal gains

A large proportion of heat gains from lighting and equipment can be reduced if energy efficient equipment is used. Reducing internal heat gains can reduce the annual energy demand in London, Hong Kong and Abu Dhabi where cooling is dominant. However, it increases the annual energy demand in Caribou offices facing North, East and West, because of its cold climate.

In Hong Kong, Abu Dhabi and Caribou, when the amount of internal gain is reduced, the effect of lowering the U-value remains the same. In Hong Kong, reduced level internal gains lead to the lower annual energy demand. The effect of lowering U-value still has a marginal effect on the energy demand. Similarly in Abu Dhabi where there is only cooling requirement throughout the year due to the high dry-bulb temperature and high solar irradiation level, reducing the amount of internal heat gains reduces the amount of cooling needs but does not change the effect of lowering the U-value. In Caribou where there is a high heating demand in winter, reducing the amount of internal gain is not good in winter, however it can reduce the cooling needs in mid-season and summer. Utilising lower U-value facade is still beneficial.

Lowering the internal heat gains from 33.7 to 25W/m² changes the effect of the U-value on the annual energy demand in offices in London. This is because the annual cooling demands are reduced but the heating demand increases due to the lower internal heat gains. Lowering the U-value saves the heating requirement and hence the annual energy demand.

8.1.2 Reducing office energy demand

The results of this study suggest that facades with low U-values and high g-values would result in energy savings in location which experience cold outdoor temperatures and low irradiation levels for prolonged periods of time. Facades with low U-values may also be appropriate in locations which experience high temperatures because they reduce conductive heat gains. But if high temperatures are accompanied by high irradiation levels then a facade with a low g-value would seem to be appropriate. These general guidelines are summarised in Table 8.2.

		High solar irradiance	Low solar irradiance	Examples
Negative ΔT	Large	Heating demand mostly, some cooling demand in South orientation	Heating demand	Winter in Caribou
		- low U, high g	- low U, high g,	
	Medium	Cooling demand dominates	A mix of heating and cooling demand	Mid-season in Caribou; winter in London
		- medium U	- medium U	
	low	Cooling demand	Cooling demand	Hong Kong winter
		- high U, low g	- high U, low g	
Positive ΔT	Small-large	Cooling demand	Cooling demand	HK mid-season and summer,
		- low U, low g	- low U, low g	
	Large	Cooling demand	Cooling demand	Abu Dhabi
		- low U, low g	- low U, low g	

Table 8.2 Design guidelines according to climatic characteristics

1) In London offices, lowering facades' g-value reduces annual energy demand but lowering facade's U-value increases the annual energy demand. Lowering offices' internal heat gains can reduce the annual energy usage. If the internal heat gains are low, lowering the U or g-value of facades would further reduce the annual energy demand. These strategies are robust under uncertainties such as longer working hours and climate change.

2) In Hong Kong offices, lowering g-values of facades reduces annual energy demand. Further reduction in the annual energy usage can be achieved by reducing internal heat gains in offices. These strategies are robust under uncertainties such as longer working hours and climate change.

3) In Caribou, utilising low U-value and low g-value facades reduce annual energy demand. This strategy is robust under uncertainties such as longer working hours, lower internal gains and climate change.

4) In Abu Dhabi offices, utilising low U and low g-value facades reduces the annual energy demand due to cooling. Further reduction in the cooling demand can be achieved by reducing internal heat gains. These strategies are robust to uncertainties such as longer working hours and climate change.

Comparing results with existing studies

The results of this study go a step further in explaining the effect of lower U-values of facades on heating and cooling loads, by highlighting the importance of ΔT . It has been found that the effect of low U-value facades on office energy demand highly depends on the magnitude of ΔT (temperature difference between the outdoors and indoors), and whether ΔT is positive or negative. The mechanisms are summarised in the following three scenarios.

1) Low U-value façades are always beneficial when outdoor temperatures are extremely cold and significantly lower than indoor temperatures; for example, in Caribou during the winter. Under these circumstances, lowering the U-value will reduce conduction heat losses and hence, reduce the energy required for heating.

2) The effect of lowering U-value is not always positive when the outdoor temperature is moderately colder than indoors; for example, mid-season and summer in Caribou, and most of the year in London. In these cases, it has been found that cooling is needed even when the outdoor temperature is lower than

the indoor temperature, because the internal heat gains and solar gains are much higher than the heat loss through conduction and ventilation. Lowering the U-value limits conduction and heat loss increases the cooling demand. However, if there are low solar heat gains and low internal heat gains, heating is needed rather than cooling, and lowering the U-value will be beneficial.

3) Low U-value façades are always beneficial when outdoor temperatures are extremely hot and significantly higher than indoors; for example, in summer in Abu Dhabi. In this case, lowering the U-value is beneficial, because it decreases unwanted conduction heat gain from outdoors to indoor areas through facades and hence, reduces the cooling demand. If the outdoor temperature is moderately higher than the indoors, for example, summer in Hong Kong, the effect of U-value is marginal.

The effect of low U-value façades on the annual energy demand depends on the climate of the test location, more specifically, the degree of season extremes. The results from London and Caribou offices showed that these two locations differ in terms of cold severity in winter. In extremely cold places, the amount of heating energy saved via a better insulated facade is higher than the cooling energy, low U-value façade generates in mid-season and summer. In a moderately cold climate, heating requirements in offices are not high. Therefore, a distinction needs to be made between a 'cool' and 'cold' climate. Designers designing offices in cool climates need to be careful regarding the use of low U-value facades, as they can increase the annual office energy demand.

Cold and temperate climates

The insights gained from this work can be used to explain the different opinions found in existing studies carried out for offices in cold climates. Grynning et al. (2013) found that the use of a high performance façade reduces the overall energy demand in Norwegian offices. Thalfeldt et al. (2013), Pikas et al. (2014) and Kim (2011) found low U-value to be beneficial in offices in cold climates, which is in line with the common perception that better insulation is preferable. Studies carried out by Raji et al. (2016) and Boyano et al. (2013) also confirm the benefits of using better insulated facades in the Netherlands and London. However, the AECOM (2011) study suggests that there is no benefit to reducing a façade's U-value in offices in the UK. Furthermore, Masoso Masoso and Grobler (2008) points out that there is a point of inflection in heat-dominating environments, where U-value increases the energy demand. Using the insights gained on ΔT from this work, low U-value can be observed as beneficial for

use in Norway and other cold environments, as the outdoor temperature is cold enough, which is the mechanism (1) noted above. However, in an environment with a cool climate such as London, which corresponds to mechanism (2), a low U-value façade will only be beneficial when the heat gains from the sun and internal environment are low.

Temperate, warm and hot climates

The insights gained from this study can also explain the different findings of warm/hot climate studies. Muhammad et al. (2016) found good insulation to be beneficial in offices in Dhahran, Saudi Arabia. A number of studies in Turkey also confirm the benefits of good insulation on the reduction of cooling demands. However, Kim et al. (2014) found that in Seoul, which has a hot and humid summer and cold winter, using a high U-value can have a positive impact on the energy demand. Tsikaloudaki et al. (2012) found an extremely low U-value unfavourable in Mediterranean zones. Based on the ΔT theory, better-insulated facades are only beneficial in conditions when the outdoor temperature is much higher than indoors, which will be the case for Dhahran, but not in cases where the outdoors is cooler than the indoors, such as in a warm climate.

In a study conducted by Masoso and Grobler (2008) it was found that in a hot climate, insulation reduces fuel consumption for cooling when the internal set point is between 21-26°C; however, it increases fuel consumption for cooling when the internal set point is above 26°C to 28°C. Although the work points out this interesting point, which contradicts the conventional understanding of insulation, it does not further explain the reasons behind the matter or its implications. When using the same method of analysis as in this project to explain this observation in Masoso and Grobler (2008)'s study, firstly, an average outdoor temperature in Botswana was found to be roughly 15°C in mid-season, and 25°C degree in summer. When the indoor temperature is set between 21-25°C, which is cooler than outdoors, conduction heat gain occurs through the façade. Hence, decreasing the U-value limits conductive heat gain and reduces cooling requirements. When the indoor temperature is raised to 26-28°C, which is hotter than outdoors, there is conductive heat loss through the façade, and better insulation stops heat from dissipating to the ambient environment. This work further confirms that the point of inflection will only occur when the outdoor environment is moderately colder than the indoor environment, and cooling is needed.

In summary, low U-value facades are always beneficial when there is a heating requirement, but its effect on the cooling energy demand depends on the magnitude of

ΔT . The results found in heating dominating offices are consistent with the literature. In cooling seasons, only when the ΔT is positive and large, will low U-value façades be beneficial. The insight about the relationship between ΔT and its effect on cooling energy demand explains the apparent contradictions found in the existing studies in cold and hot places. This insight can also potentially be helpful to design control strategies for adaptive facades.

Comments on methods

The simulation results have been processed systematically: the annual results are studied first followed by the investigations of the seasonal results. Further insights are given by looking at the seasonal temperature and solar irradiance together with the individual terms in the energy balance. It can be seen that there is a clear distinction between extreme cold, temperate cool, temperate hot, hot arid. The effect of lowering facade's U-value varies in each season because each season has its combination of temperature difference and solar radiation level. Annual performance follows the prevailing trend of seasonal performance which depends on how extreme are the summer and winter conditions.

This method of analysis provides transparency of how the important parameters interact and allows cross comparisons between different climate conditions. Interestingly, common trends can be spotted and are consistent in all cases. In the past literature, there has not been a clear explanation of the different influence of these climates which has been made clear in this study.

Building Heat Transfer

Building heat transfer has not been discussed in Chapter 4-7. Building heat transfer in TAS covers heat exchange between the target zone and other internal zones within the building and impact of thermal mass (heat stored/released in the building). A positive number means there is build-up of load overnight and the releasing of it during the day which helps to reduce the cooling load a bit. The former is zero in this model as all set points are identical. Therefore, it appears that the figures reported for this parameter are representative of the impact of thermal mass.

It is found that Q_b is more significant in winter when there is a larger temperature difference between indoors and outdoors compared to summer in some cases. For example in Abu Dhabi, the external temperatures outside operational hours are lower in winter and this will help the building fabric to cool down. In summer, it is not very

effective as the ambient temperatures are generally higher and building fabric cannot be cooled down to the same extent as in winter (from personal communication with a professional dynamic simulation tool user).

8.2 Reducing office CO₂ emissions

CO₂ emissions of the office buildings due to heating and cooling can be calculated based on the energy demand results obtained. The loads can be converted into energy consumption by applying service efficiency factors. Heating systems usually have an efficiency of 0.75 and cooling systems of 3. CO₂ emissions factors from fuel can then be applied to the amount of energy consumption to calculate the amount of CO₂ emissions.(CIBSE 2006)

Natural gas is usually used for heating and domestic hot water. Electricity is the main energy source for office lighting, equipment and cooling. Table 8.3 shows CO₂ emission factors of different fuel types. It can be seen that the CO₂ emission factor of electricity is more than double the amount of natural gas. Electricity can also be more expensive. Therefore, if the energy consumption is from these two sources, although the aim is to reduce overall energy demand, the savings in electrical energy are more desirable (Boyano et al. 2013).

Fuel	CO ₂ factor (kg/kWh)
Natural gas	0.194
Oil (average)	0.265
Coal (typical)	0.291
Electricity	0.422

Table 8.3 CO₂ factors for various fuels (Building Regulation 2006)

8.2.1 Effect of U-value on annual CO₂ emissions

In all tests performed, it has been found that lowering the g-value of the facade from 0.5 to 0.3 always reduces the annual energy demands regardless of location. Therefore, assuming g=0.3, Table 8.4 presents the heating and cooling loads, total energy demand (TED, kWh/m²) and CO₂ emissions (kg/m²) of offices facing North, East, South and West using facade with U either 1.2 W/m²K or 2.6 W/m²K in Caribou, London, Hong Kong and Abu Dhabi, under four assumed internal and external conditions. The total annual CO₂ emissions due to heating and cooling are calculated based on the conversion factors mentioned above.

a) Caribou

In Caribou, lowering the facade's U-value reduces the office annual energy demand and CO₂ emissions mainly due to the large reduction it makes to the heating load. Although it causes a rise in the cooling load, the reduction in the heating load is larger than the negative effect it has on the cooling load. This is true for offices facing all orientations. For example, utilising lower U-value facade reduces the annual CO₂ emissions by 32% in North facing offices in SC1. The effect of lowering the U-value remains the same under these conditions: it reduces the CO₂ emissions by a third.

Furthermore in Caribou, prolonging working hours increases both the heating demand and the cooling demand and therefore the total CO₂ emissions. When there is less heat gain from internal sources, the heating load is higher and the cooling is lower than those in SC1, the resulted CO₂ emissions increases by around 20%. When the future climate data is applied, there is less heating load but higher cooling demand, and resulting CO₂ emissions remains similar to those found in SC1.

b) London

In London, in SC1, SC2 and SC4, using lower U-value facades increases the annual CO₂ emissions by around 5% or has no effect at all, despite the fact that it increases the annual energy demand because of the increase in the cooling load. This is because lowering the U-value minimises the heating demand and increases the cooling demand. Although electricity has a higher CO₂ emission factor than gas, the cooling system efficiency is higher than the heating efficiency. The total heating demand is low compared with the total cooling demand in these scenarios. After applying the efficiency factor and CO₂ emission factor, the CO₂ emissions of offices using facade with U-value of 1.2 and 2.6 W/m²K are similar in SC1, SC2 and SC4. However when the internal gain is lowered, lowering the U-value of the facade reduces the CO₂ emissions.

When the working hours is extended, from 10 to 16 hours per day, the annual CO₂ emissions in the offices increase by around 55% due to the large increase in the cooling needs. The annual CO₂ emissions increase by around 20% when climate under the climate change condition. The annual CO₂ emissions can be reduced by around 20% if the internal heat gains are low, and it is robust to changes in longer working hours, climate change, longer working hours under climate change, as described in section 4.5.2, shown in Table 8.5. This further confirms the need to regulate the internal heat gain in London in order to minimize the CO₂ emissions due to heating and cooling.

c) Hong Kong

In Hong Kong, using the high performance facade increases the overall CO₂ emissions in SC1 and SC2 marginally irrespective of orientation. It makes no difference in SC3 and SC4. Because there is only cooling requirement in offices in Hong Kong all year around, the difference between using electricity or gas does not come in to play.

The annual CO₂ emissions increase when the working hours are extended or under the climate change scenario, however, they can be reduced by 25% if the internal heat gains are lowered.

d) Abu Dhabi

In Abu Dhabi, lowering the U-value of the facade reduces the annual CO₂ emissions because it reduces the annual cooling demand, around 9% of reduction can be achieved in SC1 and 6.3%, 6.8% and 8% in SC2, SC3 and SC4 respectively.

The annual CO₂ emissions increase when the working hours are extended or under the climate change scenario, however, they can be reduced by 13% if the internal heat gains are lowered.

		U	N				E				S				W			
			Heating	Cooling	T ED	CO ₂	Heating	Cooling	T ED	CO ₂	Heating	Cooling	T ED	CO ₂	Heating	Cooling	T ED	CO ₂
SC1	Caribou	1.2	31	61	92	17	28	65	93	16	21	75	96	16	27	76	103	18
		2.6	69	51	120	25	63	55	118	24	52	64	116	22	61	67	128	25
SC2	Caribou	1.2	36	93	129	22	32	99	131	22	27	110	137	22	32	110	142	24
		2.6	86	77	163	33	78	83	161	32	70	92	162	31	78	95	172	33
SC3	Caribou	1.2	57	39	96	20	53	43	95	20	43	49	93	18	51	52	103	20
		2.6	99	34	132	30	91	37	129	29	79	44	123	27	88	48	136	30
SC4	Caribou	1.2	23	76	100	17	20	81	102	17	14	93	106	17	19	93	112	18
		2.6	56	68	125	24	50	74	124	23	39	84	123	22	48	87	135	25
SC1	London	1.2	2	75	76	11	1	82	83	12	1	87	88	13	1	81	83	12
		2.6	12	57	70	11	10	65	75	12	9	70	79	12	11	65	76	12
SC2	London	1.2	1	122	122	17	0	131	131	19	0	136	136	19	0	130	131	18
		2.6	10	93	103	16	8	103	111	17	8	108	115	17	9	103	112	17
SC3	London	1.2	13	42	55	9	12	48	59	10	10	52	62	10	12	48	60	10
		2.6	32	34	66	13	29	41	68	13	25	44	68	13	29	41	70	13
SC4	London	1.2	1	88	89	13	1	96	96	14	1	103	103	15	1	97	98	14
		2.6	8	72	80	12	7	80	86	13	6	88	93	14	7	82	90	13
SC1	HK	1.2	0	148	148	21	0	151	151	21	0	159	159	22	0	160	160	22
		2.6	0	144	144	20	0	148	148	21	0	157	157	22	0	159	159	22
SC2	HK	1.2	0	222	222	31	0	225	225	32	0	233	233	33	0	235	235	33
		2.6	0	216	216	30	0	220	220	31	0	229	229	32	0	232	232	33
SC3	HK	1.2	0	110	110	15	0	113	113	16	0	121	121	17	0	122	122	17
		2.6	0	108	108	15	0	112	112	16	0	121	121	17	0	122	122	17
SC4	HK	1.2	0	164	164	23	0	166	166	23	0	175	175	25	0	174	174	24
		2.6	0	165	165	23	0	168	168	24	0	178	178	25	0	177	177	25
SC1	Abu Dhabi	1.2	0	223	223	31	0	237	237	33	0	256	256	36	0	260	260	37
		2.6	0	239	239	34	0	256	256	36	0	281	281	40	0	284	284	40
SC2	Abu Dhabi	1.2	0	316	316	44	0	330	330	46	0	351	351	49	0	356	356	50
		2.6	0	335	335	47	0	354	354	50	0	379	379	53	0	384	384	54
SC3	Abu Dhabi	1.2	0	193	193	27	0	206	206	29	0	225	225	32	0	229	229	32
		2.6	0	209	209	29	0	226	226	32	0	251	251	35	0	254	254	36
SC4	Abu Dhabi	1.2	0	249	249	35	0	261	261	37	0	280	280	39	0	282	282	40
		2.6	0	273	273	38	0	289	289	41	0	313	313	44	0	314	314	44

Table 8.4 Annual heating/cooling demand (kWh/m²) and CO₂ emissions (kg/m²) in four test locations, g=0.3

	U	N				E				S				W			
		Heatin	Coolin	Total	CO ₂	Heatin	Coolin	Total	CO ₂	Heatin	Coolin	Total	CO ₂	Heatin	Coolin	Total	CO ₂
London SC3	1.2	13	42	55	9	12	51	62	10	10	52	62	10	12	50	62	10
	2.6	32	34	66	13	29	43	72	14	25	44	68	13	30	42	73	14
London 16	1.2	31	49	80	15	30	59	89	16	28	59	87	16	31	58	88	16
	2.6	59	40	99	21	56	50	107	22	52	51	103	21	58	50	107	22
London CC	1.2	9	54	63	10	8	64	72	11	7	66	73	11	9	65	73	11
	2.6	24	47	71	13	22	57	79	14	19	59	78	13	23	58	81	14
London CC16	1.2	24	63	87	15	23	75	98	17	22	77	98	16	24	76	100	17
	2.6	46	55	101	20	45	67	112	21	41	69	110	20	45	69	114	21

Table 8.5 London Scenario 3 further tests: extended hours, climate change and extended hours with climate change

8.2.2 Effect of g-value on CO₂ emissions

Table 8.6 shows the effect of lowering the g-value from 0.5 to 0.3 when the U-value is either 1.2 W/m²K or 2.6 W/m²K in North facing offices in Caribou, London, Hong Kong and Abu Dhabi with 4 assumed conditions.

	N	g=0.3					g=0.5			
		U	Heating	Cooling	ED	CO ₂	Heating	Cooling	ED	CO ₂
Caribou	SC1	1.2	31	61	92	17	21	85	106	17
		2.6	69	51	120	25	58	68	125	24
	SC2	1.2	36	93	129	22	29	115	144	24
		2.6	86	77	163	33	77	93	170	33
	SC3	1.2	57	39	96	20	47	56	103	20
		2.6	99	34	132	30	88	46	134	29
	SC4	1.2	23	76	100	17	18	96	113	18
		2.6	56	68	125	24	49	83	133	24
London	SC1	1.2	2	75	76	11	1	94	95	14
		2.6	12	57	70	11	10	73	82	13
	SC2	1.2	1	122	122	17	0	143	144	20
		2.6	10	93	103	16	8	111	119	18
	SC3	1.2	13	42	55	9	10	60	69	11
		2.6	32	34	66	13	27	48	75	14
	SC4	1.2	1	88	89	13	1	108	109	15
		2.6	8	72	80	12	6	88	94	14
Hong Kong	SC1	1.2	0	148	148	21	0	173	173	24
		2.6	0	144	144	20	0	166	166	23
	SC2	1.2	0	222	222	31	0	248	248	35
		2.6	0	216	216	30	0	240	240	34
	SC3	1.2	0	110	110	15	0	135	135	19
		2.6	0	108	108	15	0	130	130	18
	SC4	1.2	0	164	164	23	0	192	192	27
		2.6	0	165	165	23	0	190	190	27
Abu Dhabi	SC1	1.2	0	223	223	31	0	253	253	36
		2.6	0	239	239	34	0	265	265	37
	SC2	1.2	0	316	316	44	0	347	347	49
		2.6	0	335	335	47	0	364	364	51
	SC3	1.2	0	193	193	27	0	222	222	31
		2.6	0	209	209	29	0	236	236	33
	SC4	1.2	0	249	249	35	0	279	279	39
		2.6	0	273	273	38	0	301	301	42

Table 8.6 Effect of g-values on annual heating and cooling load, total energy demand (kWh/m²) and annual CO₂ emissions (kg/m²) in North facing offices in London, Hong Kong, Abu Dhabi and Caribou

Table 8.7 shows the effect of lowering the g-value from 0.5 to 0.3 when the U-value is either 1.2 W/m²K or 2.6 W/m²K in South facing offices in Caribou, London, Hong Kong and Abu Dhabi with 4 assumed conditions.

	N	g=0.3					g=0.5			
		U	Heating	Cooling	ED	CO ₂	Heating	Cooling	ED	CO ₂
Caribou	SC1	1.2	21	75	96	16	11	120	132	20
		2.6	52	64	116	22	37	96	133	23
	SC2	1.2	27	110	137	22	20	151	171	27
		2.6	70	92	162	31	58	124	182	33
	SC3	1.2	43	49	93	18	30	81	111	19
		2.6	79	44	123	27	62	68	130	26
	SC4	1.2	14	93	106	17	8	133	141	21
		2.6	39	84	123	22	28	115	143	23
London	SC1	1.2	1	87	88	13	1	118	119	17
		2.6	9	70	79	12	6	96	102	15
	SC2	1.2	0	136	136	19	0	169	169	24
		2.6	8	108	115	17	6	136	142	21
	SC3	1.2	10	52	62	10	7	80	87	13
		2.6	25	44	68	13	19	66	86	14
	SC4	1.2	1	103	103	15	0	136	136	19
		2.6	6	88	93	14	4	116	120	17
Hong Kong	SC1	1.2	0	159	159	22	0	193	193	27
		2.6	0	157	157	22	0	188	188	26
	SC2	1.2	0	233	233	33	0	269	269	38
		2.6	0	229	229	32	0	263	263	37
	SC3	1.2	0	121	121	17	0	154	154	22
		2.6	0	121	121	17	0	151	151	21
	SC4	1.2	0	175	175	25	0	210	210	30
		2.6	0	178	178	25	0	211	211	30
Abu Dhabi	SC1	1.2	0	256	256	36	0	312	312	44
		2.6	0	281	281	40	0	333	333	47
	SC2	1.2	0	351	351	49	0	409	409	57
		2.6	0	379	379	53	0	434	434	61
	SC3	1.2	0	225	225	32	0	281	281	39
		2.6	0	251	251	35	0	303	303	43
	SC4	1.2	0	280	280	39	0	335	335	47
		2.6	0	313	313	44	0	365	365	51

Table 8.7 Effect of g-values on annual heating and cooling load, total energy demand (kWh/m²) and annual CO₂ emissions (kg/m²) in South facing offices in London, Hong Kong, Abu Dhabi and Caribou

It can be seen that in Caribou, in North facing offices when $U=1.2\text{W/m}^2\text{K}$, although lowering the g-value of the facade reduces a significant amount of energy demand mainly due to the associated reduction in the cooling demand, it has a relatively small effect on the annual CO_2 emissions in all test scenarios. However, lowering the g-value is beneficial in South facing offices in Caribou, particularly when U-value is $1.2\text{W/m}^2\text{K}$ under SC1, SC2 and SC4 conditions. However, lowering the g-value has little influence in SC3 when the internal heat gains are lowered although it reduced the annual energy demand by a large fraction. This is because of the difference in the conversion factors of heating and cooling.

In London, lowering the g-value reduces the annual CO_2 emissions in both North and South facing offices in all tested scenarios. The effect is larger in South facing offices, for example, when $U=1.2\text{ W/m}^2\text{K}$, it reduces the annual CO_2 emissions by over 24% in all test scenarios.

In Hong Kong, the effect of lowering the g-value on the annual CO_2 emissions is the same as it on the annual energy demand. For example when $U=1.2\text{W/m}^2\text{K}$, in the North facing office, lowering the g-value from 0.5 to 0.3 reduces the annual CO_2 emissions by 13%, 11%, 21% and 15% in SC1, SC2, SC3 and SC4 respectively; these values are 19%, 13%, 23% and 17% in the South facing office.

In Abu Dhabi, lowering the g-value of the facade from 0.5 to 0.3 reduces the annual CO_2 emissions because it reduces the cooling needs. in the North facing office, lowering the g-value from 0.5 to 0.3 reduces the annual CO_2 emissions by 14%, 10%, 13% and 10% in SC1, SC2, SC3 and SC4 respectively when $U=1.2\text{ W/m}^2\text{K}$; these values are 18%, 14%, 18% and 17% in the South facing office.

8.2.3 Strategies for low carbon buildings

Based on the CO_2 emissions results discussed before, strategies of using low U or low g-values, and reducing internal heat gains to reduce the overall office CO_2 emissions can be developed.

a) London

In London offices, lowering the U and g-values of the facades and the internal heat gains achieve the lowest carbon emissions.

It can be seen that the amount of CO_2 emissions depends on the nature of the energy demand, whether it is heating or cooling which determines the fuel sources and the

associated CO₂ emissions. While heating is predominantly provided by fossil fuel, electricity can be generated from a range of sources. Table 8.8 further shows the CO₂ emissions factors of electricity generated from different resources. It can be seen that electricity generated from fossil fuels has high emission factors whereas the electricity generated from the renewable energy has relatively low emission rates and is currently 50% of UK's electricity source.

combustion of fuels			CO ₂ (g/kWh)	
	natural gas		194	
	Oil		265	
	Coal		291	
Electricity generation	Overall	% UK	400	
Fossil Fuel			median	Typical ranges found
	Coal	22	880/195	700-1100/180-300 (new tech)
	Oil	<1		
	natural gas	30	480/190	400-600/180-230 (new tech)
Renewable	Nuclear	21	18	5.5-26
	Wind	30	15-40	5.2-96
	Marine		20	-20-50
	Hydro		15	2-13
	Biomass			60-285
	Solar		75	75-116
	geothermal		45	15-53

Table 8.8 CO₂ emissions of different energy sources (POST 2011)

Lowering U-value of the facade changes the proportion of the heating and cooling demand, overall energy demand and CO₂ emissions. One strategy is to utilise the renewable energy such as solar panels, at when it is the most available, even though it might increase the overall annual energy demand.

In London, the lowest energy usage occurs during winter and the highest during summer. Fortunately the solar irradiation levels follow a similar trend. This suggests that if the energy usage during winter was minimised by appropriate selection of facade type and the energy required during the remainder of the year obtained from various green sources e.g. solar panels, air source heat pumps and/or thermal piles, etc., it should be possible to make significant reductions to carbon emissions from office building in London. The energy from thermal piles could also be used in winter.

b) Hong Kong

In Hong Kong offices, lowering the internal gains and the facade's g-value reduces the annual CO₂ emissions. In Hong Kong, lowering the U-value has marginal effect on the energy demand and CO₂ emissions of buildings. Lowering g-value from 0.5 to 0.3 reduces the CO₂ emissions. If renewable energy such as solar power is used, the CO₂ emissions from offices can be further reduced.

c) Caribou

In extreme cold climatic zone, such as Caribou, offices utilising the facades with low U and g-values achieve the lowest carbon emissions. Lowering internal gains is only beneficial in South facing offices. In cold climate where the heating is high in winter and cooling is high in summer, a careful selection of the most efficient and effective renewable sources is needed.

d) Abu Dhabi

In Abu Dhabi, lowering the U-value and g-value of the facades and internal heat gains together helps the offices achieve the lowest carbon emissions. In Abu Dhabi, lowering U and lowering g both reduce the CO₂ emissions of offices. In these cities, because there are only cooling requirements in the office buildings, the differences in the heating and cooling efficiency factor does not come into play. Therefore, reducing the energy demand is directly proportional to the changes in CO₂ emissions. Installing solar panels or using electricity generated from green sources can reduce offices' CO₂ emissions.

These results also suggest that there should be a drive to develop low heat emitting office equipment and lighting for offices in hot or temperate climates.

8.3 Effectiveness of current building regulations in the UK

8.3.1 U-value limit

The amount of internal heat gains is important in office buildings, this has been shown in this study and has also been pointed out by some past literature. However, there are no specific guidelines in Building Regulations or Approved documents regarding the level of internal gains.

In the UK's building regulations, conservation of fuel and power for new buildings other than dwellings, the U-value limit for windows/curtain wall is 2.2 W/m²K. However, when

internal heat gains are high, this U-value limit is increased to $2.7\text{W/m}^2\text{K}$ for glazing/curtain wall.

As shown in the results, the variation in internal gains can reverse the effect of using a high performance facade, so there should be further guidelines for office building designs indicating the level of internal heat gains in numerical values. If it is a high internal gain office, a minimum U-value should be recommended. If it is a medium or low internal gains office, lower U-value facade would be recommended.

8.3.2 Internal set-point

In the tests conducted for London, the cooling set point has been set at $22\text{ }^\circ\text{C}$. In Hong Kong, the set point has been set as 21 to $25\text{ }^\circ\text{C}$ to reduce the energy demand and hence the CO_2 emissions. Currently, in the UK, the indoor temperature is recommended to be 20 to $22\text{ }^\circ\text{C}$ in winter and 22 to $24\text{ }^\circ\text{C}$ in summer. Given the results showing cooling is high in winter, hence, if the upper limit of the cooling set point is increased to 23 to $24\text{ }^\circ\text{C}$, which is still within the human comfort zone for both winter and summer in London, the cooling needs can be further reduced.

8.3.3 Providing design guidelines regarding internal heat gains

Checking against the CO_2 emissions based on initial simulation might not be sufficient given the current problem of 'performance gap' which is the building occupant tend to overuse the buildings. The results from the London study show that the change in internal heat gains can changes the energy efficiency of facades. The result means a correct prediction of internal gains is important for designing facade, especially when selecting facade's U-value. In the building regulations, some guidelines regarding the internal heat gains should be given. For example, around 24W/m^2 or below can be classed as low and suggest that low U-value facades should be used. Medium or high level of internal heat gains can be 34W/m^2 and above. Designers should take into account of the high possibility of higher internal heat gains than assumed to provide robust facade designs.

The current technology of low heat emitting LED lighting can reach as low as $4\text{--}5\text{W/m}^2\text{K}$. Therefore, it is possible to reach low internal heat gain offices, which is about $26.7\text{W/m}^2\text{K}$ by using LED lighting in offices in the UK. Using LED lighting can be made compulsory in the Building Regulations in the UK.

Building Regulation in other countries

In Dubai, the U-value limit for office façade is 2 W/m²K. in Abu Dhabi, regulations should encourage the use of energy efficient equipment and low u-value façade to achieve low energy buildings.

In Hong Kong, the local standard does not set the limit for the U-value for wall and it is 6.93 W/m²K in the ASHARE standard, the building survey showed the U-value of wall was between 3.4 to 5 W/m²K (Yang et al. 2008). It is important to make clear that designers do not need to reduce the façade's U-value in order to reduce the offices' energy demand. The building regulation can also encourage the use of energy efficient equipment.

In cold places such as Caribou, regulations should make clear there is no need to use low heat emitting equipment just to reduce the energy demand.

8.4 Conclusions

1. In Caribou, lowering the U-value of the facades reduces annual CO₂ emissions in offices mainly because it reduces the annual heating requirement by a large fraction. Lowering the g-value also reduces the office's CO₂ emissions except North facing offices.
2. Lowering U-value does not have much effect on London CO₂ emissions because the CO₂ emissions factor and building service efficiency are different for heating and cooling demand. Lowering the g-value can reduce energy demand and CO₂ emissions. The lowest energy usage and CO₂ emissions is achieved by a combination of lowering the U and g-value and the internal heat gains.
3. Another way to reduce CO₂ emissions in offices in London is choose a facade which would minimise the heating energy in winter and maximise cooling needs in summer when more solar energy can be harvested to generate electricity for cooling.
4. Lowering U-value does not have much effect on the annual energy demand and CO₂ emission in Hong Kong offices. Lowering the g-value reduces the annual CO₂ emissions. The annual cooling requirements and CO₂ emissions can be further reduced if the internal gains are low.
5. Lowering U-value reduces the annual cooling requirement and CO₂ emissions in Abu Dhabi offices. Lowering the g-value also reduces the annual cooling demand and CO₂ emissions. Further reduction in energy usage and CO₂ emissions can be achieved by lowering the internal heat gains.
6. Proposed changes to the UK's Building Regulations are: minimum U-value should be suggested if the internal gain is high in office buildings, increasing the set point temperature in winter to 24 degree Celsius, numerical values indicating the level of internal heat gains (low, medium and high) should be given in the UK's Building Regulations.

CHAPTER 9 CONCLUSIONS AND FUTURE WORK

Office buildings are responsible for a significant amount of energy usage and CO₂ emissions, which is undesirable because of resource depletion and/or climate change. A possible strategy for reducing energy consumption and hence CO₂ emissions might be to specify high performance facades. This project reports on an investigation on energy demand and CO₂ emissions in office buildings incorporating facades with U-values between 1.2 to 2.6 W/m²K and g-values between 0.3 to 0.5. Caribou (Maine, USA), London, Hong Kong and Abu Dhabi are selected to represent cold, cool, warm and hot locations. Other variables considered include office orientation, long working hours, low internal gains and climate change. Energy demand was calculated using a steady-state method and the dynamic simulation tool, EDSL Tas.

9.1 Conclusions

The following conclusions have been reached,

Influences of high performance facade in London offices

1. Average outdoor temperatures in London are below the design indoor temperature throughout the year yet there is an overall cooling demand in office buildings because of high internal gains.
2. Facades with U-values below the currently recommended limit of 2.2 W/m²K increase the energy required for heating and cooling in office buildings but this has little effect on offices' CO₂ emissions. However, it can reduce the energy demand and CO₂ emissions provided that the equipment and lighting produces low internal gains.
3. Longer occupancy hours increase energy demand and CO₂ emissions because internal gains persist for longer periods of time which increases the cooling needs.
4. Climate change will result in higher outdoor temperatures and solar irradiation levels which in combination increase energy demand and CO₂ emissions.
5. Significant reductions in energy usage and CO₂ emissions are possible by specifying low g-value facades as they reduce solar heat gains.
6. Energy usage is highest in summer and lowest in winter because of the solar radiation profile which exists in London.

7. A possible strategy to reduce CO₂ emissions in London offices is utilising a facade which would minimize the heating demand in winter but maximise the cooling need in summer which can be provided by using solar panels.

Proposed changes to the UK's Building Regulations

The following changes to the UK's building relations are proposed,

1. If the internal heat gains are low, a maximum U-value should be recommended whereas if the internal heat gains are high, a minimum U-value should be stated in the Building Regulation, according to the climatic condition.
2. Increase the upper limit of the set point temperature in winter from 22 to 24 °C.
3. Building regulations should provide numerical values for internal heat gains for low, medium and high level to emphasise on the effect of the performance gap on optimum U-value selection.

Influences of high performance facade in Hong Kong offices

1. Using low U-value facades has a marginal effect on the annual energy demand and CO₂ emissions in office buildings in Hong Kong.
2. Longer occupancy hours increase energy usage and CO₂ emissions and the use of low U-value facades exacerbates this condition.
3. Climate change may favour the use of low U-value facades because of generally higher outdoor temperatures. Nevertheless the benefits appear to be marginal.
4. The highest energy demand occurs in summer and the lowest in winter. Except for south facing offices this pattern of energy demand coincides with the pattern of solar radiation and maximises the possibility of sourcing the energy necessary for cooling of offices in Hong Kong from solar power.
5. Low g-value facades can reduce energy usage by up to 25% which is comparable with the energy savings possible by using equipment and lighting with lower internal gains.

Influences of high performance facade in Caribou offices

1. In Caribou where the climate is cold in winter, the use of low U-value facades can reduce the annual energy demand and CO₂ emissions irrespective of office orientation, and even facing uncertainties such as longer working hours, lower internal gains and climate change, because it reduces a large amount of heating demand in winter.
2. The better insulation changes the proportion of heating and cooling required, the annual cooling demand is higher than the annual heating demand.
3. Lowering g-value of facade also reduces the energy demand and CO₂ emissions in Caribou offices, however its effect is less than that of lowering U-value.
4. Longer occupancy hours increase offices' energy demand and CO₂ emissions because it increases both the annual heating and cooling requirements.
5. When the internal heat gains are reduced, the annual energy demand and CO₂ emissions in offices increases by a small amount because of the cold climate.
6. Climate change will result in higher outdoor temperatures and solar irradiation levels which in combination increase energy demand because of reduced conduction heat losses and higher solar gains.
7. The office annual energy demand is the lowest when a low U and low g-values facade is used.

Influences of high performance facade in Abu Dhabi offices

1. In Abu Dhabi, where the averaged outdoor temperatures are significantly hotter than indoors, the combined effect of the high outdoor temperature with the high solar irradiance and internal heat gains is that there is high cooling demand all year around.
2. Reducing the U-value of the facade reduces offices' annual cooling demand and CO₂ emissions because it reduces unwanted heat infiltration.
3. Utilising facades with low g-value reduces the associated solar heat gain and the annual cooling demand and CO₂ emissions all year around.
4. Therefore, it is better to use facade with low U and low g facades. This strategy is robust to changes such as longer working hours, lower internal heat gains and climate change.

5. In general, longer working hours increase energy usage for cooling and CO₂ emissions.
6. Lower level internal gains under normal working hour condition decreases the office cooling requirement and hence CO₂ emissions, because of the reduction in the internal heat gain.
7. Climate change causes an increase in outdoor temperature and hence an increase in office' annual cooling requirement and CO₂ emissions.

9.2 Future work

1. In order to generalize the results, more locations are needed.
2. Further investigation of optimizing the use of renewable energy, i.e. investigate the seasonal availability of renewable energy and then choose a U-value which would give the most appropriate offices' heating and cooling demand proportion.
3. Optimise offices' internal heat gains in heating dominating places.
4. Optimise building shape.
5. Work out the threshold of internal heat gains which would cause a change in effectiveness of using lower U-value facades, particularly in climates which a mix of heating and cooling.

9.3 Contributions of this thesis

The contributions to knowledge in this thesis are:

- 1) Analysed the effect of high performance facade on heating and cooling energy demand and CO₂ emissions in offices under four climatic conditions.
- 2) Detailed and systematic seasonal analysis unpicks some of the apparent contradictions found in results relating to climate which generate a new way of results interpretation.
- 3) Tested uncertainties such as variation in work patterns and climate change which are the two biggest challenges faced by the building design industry.
- 5) Proposed improvement to the UK's Building Regulations.
- 4) Gave suggestions of low energy demand and low carbon office design guidelines under a range of climate conditions.

APPENDIX

1. London, worked Example

Work out the energy demand of London in winter under the current climate condition for North orientation. Use the same method to work out energy demand for mid-season and summer. Hence work out the annual energy demand for the office module facing South orientation. Table 0.1 summaries all the design information.

Input information

Floor Area, m ²	60
Volume, m ³	180
External wall area, m ²	30
Glass pane area, m ²	21
Opaque wall area, m ²	9
Opaque wall U-value, W/m ² K	1.2
Glass U-value, W/m ² K	1.2
Glass g-value	0.5
Seasonally mean outdoor temperature, °C	5.8
Design indoor temperature, °C	22
ΔT, °C	-16.2
Seasonally daily mean solar irradiance (South), W/m ²	57.9
Length of occupied period, hour	10
Days in the week, day	7
Air exchange rate, N, (Ventilation rate and infiltration rate), ach	1.2

Table 0.1 Values of input parameters in steady state calculation example

Step 1 Conduction gain/loss

$$Q_{\text{cond}} = \Delta T \sum_k U_k A_k = (-16.2) \times 1.2 \times 30 = -583.2 \text{ W}$$

Step 2 Ventilation gain/loss

$$Q_{\text{air}} = 1/3 NV\Delta T$$

$$= 1/3 \times 1.2 \times 180 \times (-16.2) = -1166.4 \text{ W}$$

Average to 24 hour rate

$$Q_{\text{air}} = (-1166.4 \times 10)/24 = -486 \text{ W}$$

Step 3 Solar gains

$$Q_{\text{sol}} = S \times A_g \times g$$

$$= 57.9 \times 21 \times 0.5 = 607.95 \text{ W}$$

Step 4 Internal gains

$$Q_{\text{int,peak}} = (Q_{\text{occ}} + Q_{\text{equ}} + Q_{\text{lit}})$$

$$= (6.7 + 12 + 15)$$

$$= 33.7 \text{ W/m}^2$$

10 working hours rate

$$Q_{\text{int}} = 60 \times (33.7 \times 10)/24$$

$$= 840 \text{ W}$$

Step 5 Total load

$$\text{Summing up} = (-534.6) + (-486) + 607.95 + 840 = 427.95 \text{ W}$$

Results generated from Tas is in kWh/m² which will be explained later, hence, here the results are converted to kWh/m² to make cross comparison easier. Assuming winter has 121 days, hence energy demand in kWh/m² is

$(427.95 \times 24 \times 121) / (60 \times 1000) = 20.7 \text{ kWh/m}^2$, positive sign indicates there is a net heat gain and the cooling energy required is 20.7 kWh/m².

	U	South (kWh/m ²)				
		Q	Q _{cond}	Q _v	Q _{int}	Q _{sol}
W	1.2	19	-28	-23	41	30
	2.6	-14	-61	-23	41	30
M	1.2	56	-20	-17	41	52
	2.6	32	-44	-17	41	52
S	1.2	81	-10	-8	41	57
	2.6	70	-20	-8	41	57

Table 0.2 g=0.5 seasonal energy demand from steady state calculation

2 London Tas results example

Once all the essential information has been fed into the model, simulations can be performed. TAS can simulate hourly building energy performance over a year. Breakdown hourly data and results can be obtained from TAS Results Viewer. Tas produces hourly results for 365 days, 24 hours per day and hence there are 8760 data points in total.

There are 8760 values for each output parameter. The version used for this study are student licence.

Output data are:

- Heating and cooling load for each zone and whole buildings
- Breakdown loads

These detailed results can be viewed in TAS results viewer.

The screenshot displays the 'Tas Result Viewer' application. The interface includes a menu bar (File, Edit, View, Tools..., Help), a toolbar with icons for file operations, and a left-hand navigation pane with a tree view containing categories like 'Simulation Data', 'Heating Design Data', 'Cooling Design Data', 'Output Selection', and 'Output Filters'. The main workspace shows a 'Start Day' of 1 and 'End Day' of 365, with an 'Output Selection' dropdown set to 'All Zones'. Checkboxes for 'Simulation Results', 'Heating Design Data', and 'Cooling Design Data' are visible, along as 'ACH' and 'External' options. Below these are tabs for 'Graphical', 'Tabular', 'Graphical Sum', and 'Tabular Sum', with 'Tabular' currently selected. The central area contains a large table with 12 columns representing different energy metrics and 20 rows of data. The columns are: 01North Heating Load (W), 01North Cooling Load (W), 01North Solar Gain (W), 01North Lighting Gain (W), 01North Int/Ext Gain (W), 01North Air Movement Gain (W), 01North Building Heat Transfer (W), 01North External Conduction Opaque (W), 01North External Conduction Glazing (W), 01North Occupancy Sensible Gain (W), and 01North Equipment Sensible Gain (W). The first column also includes a sub-column for zone identification (e.g., 1, 1; 1, 2; ... 1, 20). The table shows numerical values for each metric across the 20 rows, with some values being zero and others showing significant energy loads or gains.

	01North Heating Load (W)	01North Cooling Load (W)	01North Solar Gain (W)	01North Lighting Gain (W)	01North Int/Ext Gain (W)	01North Air Movement Gain (W)	01North Building Heat Transfer (W)	01North External Conduction Opaque (W)	01North External Conduction Glazing (W)	01North Occupancy Sensible Gain (W)	01North Equipment Sensible Gain (W)
1, 1	0.00	0.00	0.00	0.00	-0.00	0.00	439.47	-65.27	-374.20	0.00	0.00
1, 2	0.00	0.00	0.00	0.00	-0.00	0.00	432.77	-62.92	-369.85	0.00	0.00
1, 3	0.00	0.00	0.00	0.00	-0.00	0.00	442.12	-61.36	-380.76	0.00	0.00
1, 4	0.00	0.00	0.00	0.00	-0.00	0.00	433.63	-61.06	-372.57	0.00	0.00
1, 5	0.00	0.00	0.00	0.00	-0.00	0.00	425.43	-60.14	-365.29	0.00	0.00
1, 6	0.00	0.00	0.00	0.00	-0.00	0.00	407.86	-59.12	-348.53	0.00	0.00
1, 7	0.00	0.00	0.00	0.00	-0.00	0.00	383.14	-57.44	-325.70	0.00	0.00
1, 8	0.00	0.00	0.00	0.00	-0.00	0.00	356.67	-55.28	-301.38	0.00	0.00
1, 9	361.34	0.00	29.34	694.86	-909.42	0.00	-978.73	-95.72	-358.19	387.96	868.57
1, 10	0.00	140.91	66.68	694.86	-855.40	0.00	-601.02	-76.77	-343.96	387.96	868.57
1, 11	0.00	210.28	112.02	694.86	-868.87	0.00	-559.00	-88.87	-356.38	387.96	868.57
1, 12	0.00	251.22	138.89	694.86	-875.61	0.00	-539.11	-65.32	-358.81	387.96	868.57
1, 13	0.00	318.85	138.89	694.86	-841.93	0.00	-518.42	-62.84	-348.05	387.96	868.57
1, 14	0.00	408.20	117.35	694.86	-781.31	0.00	-495.25	-60.19	-323.79	387.96	868.57
1, 15	0.00	456.76	74.68	694.86	-747.63	0.00	-457.06	-57.02	-307.59	387.96	868.57
1, 16	0.00	486.16	40.01	694.86	-727.42	0.00	-424.14	-54.52	-299.16	387.96	868.57
1, 17	0.00	529.38	0.00	694.86	-693.74	0.00	-392.49	-52.46	-283.30	387.96	868.57
1, 18	0.00	571.53	0.00	694.86	-666.79	0.00	-384.86	-50.74	-277.45	387.96	868.57
1, 19	0.00	0.00	0.00	0.00	-0.00	0.00	282.12	-28.22	-233.89	0.00	0.00
1, 20	0.00	0.00	0.00	0.00	-0.00	0.00	231.83	-29.26	-202.57	0.00	0.00

Seasonal summation

Heating load and cooling load is the summation of the rest of the columns. It can be seen that air movement gain is 0 because there is no window openings

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