STUDY OF OPTIMAL COMMERCIAL BUILDING ENVELOPE DESIGN IN COOLING-DOMINANT CLIMATES

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Study of Optimal Commercial Building Envelope Design in Cooling-Dominant Climates

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Abstract of thesis entitled: Study of Optimal Commercial Building Envelope Design in Cooling-Dominant Climates

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Energy consumed by buildings is an important part of total energy consumption. Energy-efficient building design and retrofitting have attracted the attention of building professionals all over the world. Heat transfer through the building envelope is a major factor that affects the air-conditioning energy consumption of a building. It is believed that a well-designed building envelope could significantly contribute to the energy efficiency of a building. Due to the relatively complex climate factors, building envelope designs in different areas are quite different. The primary aim of this study is to develop a comprehensive evaluation of the energy properties of common building envelope designs for commercial buildings in cooling-dominant climates, so as to provide a practical reference for energy-efficient building design and retrofitting. The evaluation takes into consideration both thermal and daylighting performance. A series of simulation works were conducted. Insulation against wall area, transparent insulation against window areas as well as applications of shading devices were investigated and discussed. Four cities with different latitudes, namely Singapore, Hong Kong, Houston and Maimi were selected. The impact of envelope orientation and building type were also considered.

In cooling-dominant climates, heat gain through window areas is mainly caused by the transmission of solar radiation, thus reducing unwanted solar radiation is a promising way to reduce energy consumption. First, an experiment was conducted to study the actual thermal performance of the interior blind in Hong Kong. An office room facing east was selected. During a clear sunny day when the tilt angle of the blind louver stayed at 90°, heat gain through the envelope was reduced by around 9%. Secondly, an EnergyPlus simulation based on the same office room was also finished. A gerenally satisfactory agreement was achieved between the experiment and the simulation results. Thirdly, the two most popular shading designs, namely the interior blind and the overhang on an office building were investigated. A series of simulation tests were carried out to further analyze the thermal performance of the interior blind and the overhang shading designs. The results show that with the application of the internal blind, annual solar radiation heat gain through the window areas can be reduced by at least 20%. With the application of an overhang, a reduction of over 40% can be expected. The orientations and geographic locations have a significant influence on the devices' shading effects. Shading devices on the east and west facades reduce the most solar heat gain, while devices on the north façade reduce the least. In cooling-dominant climates, the contribution of the north facing shading device cannot be ignored. As the latitude rises, interior and exterior shading devices on the north façade made a smaller difference. Occupants' behaviors could significantly affect the performance of the blind. Setting the slat angle at 90° could only reduce window heat gain by about 15% to 20%, while setting the slat angle at 30° could achieve a reduction of around 40% to 50%. It was also discovered that a further increase of overhang depth does not affect the performance of the overhang significantly when the overhang depth exceeds half of the window's height.

A series of simulation studies were also carried out to research the practicality of different advanced glazing materials in cooling-dominant climates. Single-layer glass with different thicknesses, double-layer glass with different gas layers and low-e glass with different thermal parameters were considered. Results show that when the thickness of a single-layer glass changes from 6mm to 12mm, the thermal performance of the single-layer glass remains almost unchanged. Double-layer glass could reduce heat gain through window areas by 15%~20%. Due to its low solar transmittance, low-e glass performs better than double-layer glass. When low-e glass with a solar transmittance of 0.59 is used, solar heat gain could be cut by around 40%. If low-e glass with a lower solar transmittance is selected, an even larger reduction can be expected. Besides, orientation would affect the performance of glazing materials significantly. Advanced glazing materials applied on the east and west window areas could reduce more solar heat gain by around 20% than those on the south and north window areas.

In order to obtain a comprehensive evaluation on the overall energy performance of energy-efficient building envelope designs, daylighting simulation work was also carried out to study the lighting energy reduction when a daylighting strategy was applied to commercial buildings, and based on the same building model for the thermal simulation. Results indicate that energy savings from daylighting on low-e glazing and double-layer glazing are almost the same on all orientations (around 1.7% in office buildings, 0.8% in hotel buildings). Considering its better thermal insulation effect, low-e glazing is generally the best choice among all glazing materials. Daylighting performance of overhang shading is not different to that of glazing materials. With respect to the interior blind, lighting energy saving is significantly lower (0.7% to 1.6% in office buildings). Orientation and geographic locations also have clear affects. All the envelope designs perform better on the east and west orientations. In areas with low latitude, the difference among orientations is significant, and energy-efficient designs on east and west façades can reduce solar heat gain by more than 50% than those on the south and north facades. As latitude rises, the difference is only around 10%.

For the assessment of energy-efficient retrofitting projects, apart from the annual saving of actual values and economic payback time, energy and CO_2 emission payback periods should also be taken as indispensable references. A case study involving a life-cycle and pay-back period analysis of the energy and CO_2 emission was conducted for the addition of external overhang shading as energy efficienct retrofitting in a university campus in Hong Kong. Results indicate that although introducing an overhang shading system could reduce almost half of the cooling load in the related area, the energy and CO_2 emission payback periods of the project were still unrealistically long due to the requirements of structural strength under typhoon situations. This case study presents an example of a multi-disciplinary approach being not only important to energy-efficient retrofitting projects but also necessary for policy making in different climatic and geographic regions.

Finally, another series of simulation work was also practised to investigate the performance of the two most popular insulation methods on wall surfaces, namely thermal insulation and high-reflectivity coatings on commercial building walls in cooling-dominant climates. Results show that in cooling-dominant climates, the implement of thermal insulation on wall areas could receive an at least 80% reduction in solar heat gain through external walls. The effects of insulation measures vary with the wall orientations. Insulation on the east and west walls can receive around 10% more reduction than that on the south wall. Wall insulation on the north orientation could only achieve an about 50% profit compared with those on the east and west orientations. In climates with little diurnal temperature change in the summer season when air-conditioning systems operate during the daytime only, internal insulation performs 20% better than external insulation in reducing the air-conditioning load, whereas in climates in which there is a free cooling period during the night, a 20% more reduction can be expected from external insulation.

In conclusion, in this thesis, a comprehensive study was conducted to assess the thermal and daylighting performance of popular energy-efficient building envelope designs, so that an optimal envelope design can be achieved for commercial buildings in cooling-dominant climates. The result arising from the thesis further emphasizes the significance of building envelope design in cooling-dominant climates. In cooling-dominant climates, energy-efficient building envelope designs on the east and west orientations can achieve a better profit than those on the north and south orientations. In low-latitude area, the difference of performances among envelope designs on the different orientations is quite signifincat. As the latitude rises, the difference become smaller. Internal shading device is also a practical shading alternative. In many cases, internal shading can perform as well as external shading. The adjustability of internal shading enables occupants to retain a more comfortable thermal and visual environment, which cannot be achieved by external shading. Especially in the area like Hong Kong where typhoon strikes a lot in summer, internal shading is prefered. Appropriate insulation on external wall can also achieve a better thermal performance in cooling-dominant climates.

PUBLICATIONS ARISING FROM THE THESIS

I. Journal Papers

- **Yu Huang,** Jian-lei Niu, Tse-ming Chung, Study on performance of energy-efficient retrofitting measures on commercial building external walls in cooling-dominant cities, Applied Energy, 2013, 103: 97-108. (Based on Chapter 7)
- **Yu Huang,** Jian-lei Niu, Tse-ming Chung, Energy and carbon emission payback analysis for energy-efficient retrofitting in buildings-Overhang shading option, Energy and Buildings, 2012, 44: 94-103. (Based on Chapter 6)

II. Manuscripts

- **Yu Huang,** Jian-lei Niu, Tse-ming Chung, Study on Thermal Performance of Internal Blinds on Office Building Envelope in Cooling-Dominant Climates. Submitted to Journal of Building Performance Simulation. (Based on Chapter 4)
- **Yu Huang,** Jian-lei Niu, Tse-ming Chung, Comprehensive Analysis on Thermal and Daylighting Performance of Glazing and Shading Designs on Office Building Envelope in Cooling-Dominant Climates. Submitted to Applied Energy. (Based on Chapter 4 & 5)

III. Conference Papers

- **Yu Huang,** Jian-lei Niu and Tse-ming Chung, Lfie cycle analysis for an overhang retrofitting project of buildings in Hong Kong, in 7th International Symposium on Heating, Ventilating and Air Conditioning Proceedings. 2011. Shanghai, PR. China. (Based on Chapter 6)
- **Yu Huang,** Jian-lei Niu and Tse-ming Chung, Experimental Study on Performance of Interior Blind in Office Buildings in Hong Kong, in 13th

International Conference on Indoor Air Quality and Climate, July 2014, Hong Kong, Paper ID: HP0051. (Based on Chapter 3)

- **Yu Huang,** Jian-lei Niu and Tse-ming Chung, Simulation Study of Shading Design Performance in Office Buildings in Cooling-Dominant Climates, in 13th International Conference on Indoor Air Quality and Climate, July 2014, Hong Kong, Paper ID: HP0052. (Based on Chapter 4)

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Chapter 1

Introduction

1.1 Background

Building is the most important and indispensable part of a human being's life. Normally, people will spend 70% to 90% of their life time in buildings. According to the study of Perez-Lombard et al. (2008), buildings account for more than 40% of all the energy and almost 50% of the CO_2 emissions in most developed economies throughout the world, and an increasing proportion in many developing and emerging economies. It is believed that with the developing of economy and urbanization, the proportion of building energy consumption will keep growing rapidly. Reducing building energy consumption is a huge contribution to the present society as well as the future generation.

Since last century, particularly after the "oil crises" of the late 1970s and 1980s, the implications of our dependence on fossil fuels have created a marked awareness of the need to conserve energy and to discover new sources of energy across the society. Building energy management is considered to be one of the most direct and effective way to relieve the energy shortage. It is not hyperbole to suggest that a better building design could result in a reduction of 50% to 75% in the building's energy consumption, and that appropriate intervention would also result in a reduction of up to 30%, which could significantly reduce the energy consumption all around the world and contribute to environmental impact and climate change (Ürge-Vorsatz, 2007). Of the total energy consumption from buildings, the energy consumed by HVAC and lighting systems accounts for a large proportion. Reducing energy consumed by these systems is a major issue concerned by building professionals.

Energy consumed by the HVAC systems accounts for over 40% of the total energy consumption in buildings (Yu & Chow, 2001). A large amount of energy is utilized to handle the system load caused by the heat transfer through building envelopes. Optimizing the energy performance of building envelope is considered to be a promising way to reduce the energy consumption of HVAC system, therefore becomes a hot research area. Building envelope serves as a separation of building inside environment from outside environment. Normally, building envelope could block out thermal transmission and natural lighting, thus maintain a relatively independent indoor artificial environment. The design of building envelopes can largely affect indoor thermal and visual environment, therefore affect the energy performance of buildings. Besides, heat gain through building envelope and cooling load caused by artificial lighting system form a large part of space cooling load handled by the HVAC system.

Daylight is often considered to be the best source of light for its good colour rendering and closely matches with human visual response. Daylight can make an interior space look more attractive. The daylight entering a building through windows provides the dual function not only of admitting light into the indoor environment, but also in connecting the outside world to the inside of a building. People expect good natural lighting in their working places, which will also improve their working efficiency (Roche et al., 2000). A well designed building envelope could block out unwanted heat gain by solar radiation and thermal transmission and still provide substantial daylighting at the same time, so as to reduce inner space cooling load.

1.2 Statement of the Problem

There have been a large number of studies on building envelope insulation in high-latitude areas. With respect to low latitude area, the research is very limited. In cooling-dominant areas, conventional thinking does not pay much attention on the thermal performance of building envelope design. Designers tend to make the thermal inertia of building envelope small to strengthen the heat transfer process. Besides, the majority of existing studies on building envelope takes the envelope as a whole, while the impact of orientation is ignored.

As building energy efficiency becomes a popular topic, it should also be noticed that most existing buildings were built late last century, when building energy consumption was not a concern. These buildings will still be occupied until 2025 or even 2050 (Diana et al., 2007). It is clearly not realistic to demolish all these buildings to get new energy-efficient ones. Conducting cost-effective retrofits on existing buildings is considered to be a necessary measure to reduce building energy consumption currently. As the living standard rises, building users will have their own way to maintain better comfort inside their buildings, and installing electric heaters and air conditioners are common practices.

But now it is also increasingly recognized that cost-effective retrofits of building envelopes is becoming the only acceptable way to reduce building energy consumption. It is reported that a reduction of up to 75% could be expected from retrofitting of existing commercial buildings (Ürge-Vorsatz et al., 2007). The majority of existing studies focus on the thermal property of building materials and building styles. Little attention has been paid on retrofitting of existing buildings.

Due to its multiple advantages, daylighting has become a common design element on building envelope. However, application of daylighting could also bring in unwanted solar radiation at the same time, which could result in an increasing in space cooling load. There have been a large number of studies on the thermal performance and the daylighting performance of building envelope, but not many researchers notice the comprehensive performance of these two factors.

1.3 Structure of the Thesis

This thesis consists of 8 chapters that include the introduction of the thesis, a literature review of the existing related research on the performance of commercial building envelope in cooling dominant climates, and a case study of a life cycle analysis on an overhang shading system in Hong Kong that is based on a practical project. The contents in each chapter are summarized as follows:

Chapter 1 introduces the background and the motivation of this research and provides an overview of the whole thesis.

In Chapter 2, related existing studies are extensively reviewed, including studies on both thermal and daylighting performance of building envelope. Literatures on both wall and window research are collected and discussed. The significance of this study is also discussed.

In Chapter 3 the research methodologies utilized in this study are presented. A world famous building energy simulation program EnergyPlus is applied in the thermal simulation study. Based on dynamic characteristics of the space load, EnergyPlus uses state-space method to model heating, cooling, lighting ventilation and other energy flows in building. Another famous daylighting simulation program Daysim is applied in daylighting simulation. The basic calculation principles used in EnergyPlus and Daysim is briefly listed and introduced. An on-site measurement on the interior blind application in an office building in Hong Kong was carried out. The layout of the target office room and the positions of measuring points for the on-site measurement were described. The results of the on-site measurement on the interior blind performance are presented. Measurement results are also compared with simulation result to enhance the credibility of EnergyPlus simulation.

Chapter 4 presents the analysis results of the thermal simulation of both glazing and shading alterations. The thermal properties of building materials are presented in detail.

The schedules for occupant, lighting, electricity equipment and AC system under different building functions are also listed. The thermal properties and structural parameters of proposed devices are also detailed listed. For the simulation study, a common high-rise building model was built. The distribution of monitoring points is also described. For the glazing alterations, several glazing materials, namely single-layer glass, multi-layer glass and low-e glass were considered. The annual energy consumption and the peak cooling load were calculated. The effects of orientation, climate and building function are discussed. The influence of material properties is considered. The affection of occupant behaviour on interior blind is discussed.

Chapter 5 presents a case study involving a practical overhang shading retrofitting project in a university campus in Hong Kong. The details of the design and construction are listed. A life-cycle analysis and payback period calculation of the energy and CO_2 emission are described.

Chapter 6 presents the analysis results of daylighting performance of both glazing and shading alterations. Annual energy saved from the lighting system was calculated. The impacts of orientation and climate are discussed. The impact of material properties is also considered. The influence of occupant behavior on the interior blind is presented.

Chapter 7 presents the simulation results of the two different wall insulation alterations in cooling-dominant climates. The affections of orientation, climate and building function are discussed. The impact of material properties was also considered. Reduction of the annual energy consumption and the peak cooling load were calculated.

The final chapter, Chapter 8 presents the general conclusion drawn from the work. The limitations of the existing work are presented. Suggestions for future research are also proposed.

Chapter 2

Literature Review

2.1 Research on Thermal Performance of Building Envelope

2.1.1 Introduction

Building envelope serves as a separation of building inside environment from outside environment. Normally, building envelope blocks out thermal transmission and natural lighting, thus maintain a relatively independent indoor artificial environment. The design of building facades would largely impact indoor thermal and visual environment, and therefore affect the energy performance of a building.

Energy consumed by HVAC system accounts for over 40% of the total energy consumption in buildings (Yu & Chow, 2001), and a large amount of energy is utilized to handle system load due to heat transfer through building envelope. Optimizing the energy performance of building envelope is considered to be a promising way to reduce the energy consumption of HVAC system, therefore becomes a hot research area with many researchers involved in.

2.1.2 Insulation against External Wall Area

The most commonly used wall materials include wood, metal and masonry. Ozel (2011) studied the thermal performance of different building structure materials in tropics area, and claimed that the optimum insulation thickness for different building structure materials varied from 2 to 8.2 cm.

Besides, many other types of advanced wall designs and technologies have been applied to improve the energy efficiency and comfort levels of building walls. Since its first designed and fulfilled, Trombe wall has become a common style as passive solar wall design. Trombe wall could make full use of solar heat without extra heat storage system, and could also be coupled with many other technologies, thus has been a hot topic in building energy research area (Ji et al., 2009; Sharma et al., 1989; Zalewski et al., 1997; Zalewski et al., 2002). Ji J et al. (2009) introduced a Trombe wall system with steel panel backed with polystyrene insulation mounted on the south façade, which was said could improve the efficiency by 56%. Ji et al. (2007) alsdo proposed a PV integrated Trombe wall, and claimed that the indoor temperature could increase by 7.7℃, while the electrical efficiency of the PV could reach 10.4%.

Phase change material (PCM) is also a very hot research topic for building wall materials. Zhang et al. (2007) conducted a very detailed review of PCM application for latent thermal energy storage in buildings, and summarized the advantages of the application: narrowing the gap between the peak and off-peak loads of electricity demand, saving operative fees by shifting the electrical consumption from peak periods to off-peak periods, utilizing solar energy continuously to improve thermal comfort, and reducing air-conditioning cooling load. Diaconu (2011) studied the influence of occupancy pattern and ventilation on energy performance of PCM walls, and claimed that the occupancy pattern influences the value of the PCM melting point for which the max energy savings was reached, and that the ventilation and its pattern reduced the energy performance of PCM walls.

Another very common wall design is double-skin façade, which is a wall style with an air gap between two layers of wall skins. There are two basic kinds of ventilated walls, one with force ventilation in the cavity and the other one with natural ventilation. Double-skin façade could help to enhance the passive cooling of buildings in summer. In winter, the ventilation could be shut down so that the façade could serve as a kind of insulation. Safer et al. (2005) studied the air flow situation within a double –skin façade using CFD simulation tool, and found that the distance between the blind and the external glazing have a major impact on the velocity profiles inside the façade channel. Fallahi et al. (2010) simulated the energy performance of double-skin façade and received a energy saving of 21%- 26% in summer and 41%- 59% in winter. Perez-Grande et al. (2005) investigated the influence of glass properties on the performance of double-skin facades, and found that the performance of double-skin façade is very sensitive to external solar irradiation and with the radiation transmission coefficient of the glass increased while the performance of the double-skin façade decreased. Chan et al. (2009) also studied the energy performance of double-skin façade in Hong Kong and claimed that the annual saving of 26% could be achieved, but the payback period could be as long as 81 years, thus they thought that double-skin facades are not applicable in everywhere in the world.

Recently, a new design of building façade style has become more and more popular all over the world: plant-covered wall, or “green wall”. Vegetation is planted on the external wall surface as a layer of building envelope. Plants could absorb a considerable part of heat from external environment, and block out a significant proportion of solar radiation, the leaf transpiration could also bring in a cooling effect, so that the temperature of the surface could be reduced significantly, Moreover, green wall could weaken the sound pollution in cities, filter and purify the atmosphere by dust absorption. The life of wall could also extend. Eumorfopoulou & Kontoleon (2009) developed an experimental approach to test the contribution of plant-covered walls to the thermal behavior of building envelopes, and discovered that the mean temperature of plant-covered wall is about 1℃ lower than normal walls. Alexandri & Jones (2008) also discovered that with the application of green wall, the surface temperatures of the walls would drop significantly, respectively 4.4℃ for the outer surface and 0.9℃ for the inter surface.

In cooling dominant climates cooling load caused by heat transfer through opaque surface of building envelope could mainly be traced into two sources. One is radiation, including solar radiation, sky radiation as well as other radiation reflected by surrounding environment. The other one is convection heat transferred from external air to the building envelope. There are also two major measures to improve the thermal performance of building external wall. One is reducing thermal energy absorbed by external surface. Therefore in practical retrofitting projects the most common approach is reducing the radiation heat gain by increasing the reflectivity of building surface or introducing shading. The other one is raising the thermal resistance of external wall, which is mainly achieved by the installation of insulation materials (Ürge-Vorsatz, 2007).

The application of shading system could be dated back to several thousand years ago, when civilization began. Appropriate shading could bring significant reduction on solar radiation heat gain. There have been numerous studies on shading related researches. In the past twenty years, another way of reducing radiation heat gain was brought into people's sight. In the late 1990s, researchers in the US started to notice the contribution of reflective roofs to the energy consumption reduction. Akbari et al. (1997) tested the electricity savings in several commercial buildings with high-albedo coating on roofs, and reported a significant reduction in cooling energy. After several years of monitoring, Parker & Barkaszi (1997) reported the electricity saving of 9 residential buildings with their roof whitened. They claimed that the energy savings range from 2% to 43% due to different building structure and AC system sizing and operation schedules. With the help of DOE-2 program, Akbari et al. (1999) simulated the energy savings potential of reflective roofs for residential and commercial buildings in the US, and claimed that if the present roofs were changed to optimum reflectivity, the total saving could be up to about $ 750 million.

Early researches on high reflectivity roof were mainly on-site reports of projects, after 2000, researchers started some very interesting and systematic studies. Granja & Labaki (2003) provided a method for calculating roof heat gain under different reflectance. Levinson et al. (2007) believed that difference of solar absorption would cause proportional changes in ceiling heat flux. Suehrcke et al. (2008) conducted an interesting study in Australia. They were able to give an R-value to the reflectivity of a roof surface and suggested that in hot climates a significant reduction in downward heat flow could be achieved by using reflective roof. Levinson et al. (2005) studied the affect caused by reduction of reflectance due to aging and weather and claimed that the roof solar reflectivity could drop seriously in 5~8 years, and washing could almost completely restore the original reflectivity. Kolokotroni et al. (2011) conducted experimental and simulation study on the temperature drop rate caused by cool roof technology. They declared a 2.5℃ difference in operative temperature could be achieved in naturally ventilated buildings and a reduction of heating and cooling demand of 1% to 8.5%. Romeo & Zinzi (2011) studied the cool roof application under Sicilian climate. They found that different structure and purpose of buildings could affect the performance of cool roof technology. Scherba et al. (2011) presented a study on the impacts of roof systems on sensible heat flux into the urban environment. They claimed that a white or green roof could be a good choice for better urban environment. Shen et al. (2011) conducted an experimental study on high reflective coating in Shanghai and discovered that although it could save large amount of energy in summer, the heating demand in winter also increased. They also suggested that the performance of the coating is affected by the thermal resistance of the material.

In regions with high latitude, building insulation had been widely applied for quite a long time, due to heating requirement during cold winter. Jelle (2011) made a very detailed summary on the researches on insulation materials and solutions. In cooling dominant regions, the effect of building insulation on energy consumption has just been noticed recently. Bojic & Loveday (1997) conducted a simulation study on the building thermal behavior, and noticed that insulation could help to reduce energy consumption in buildings. With the application of DOE-2 software, Lam (2000) reported that in subtropical climates, increasing the overall thermal transfer value (OTTV) could contribute to the energy performance of commercial buildings. By employing HTB2 software, Bojic et al. (2001) studied the influence of internal versus external thermal insulation on the energy performance of high-rise residential buildings in Hong Kong, and claimed that performance of interior insulation is slightly better than external surface insulation. In another study, they suggested that a 50mm thick thermal insulation layer is optimal, and increasing the thickness beyond 50mm would only lead to a small further reduction in cooling load (Bojik et al., 2002). Al-Homound (2005) also presented his work on some detailed processing in practical work that may affect the performance of building thermal insulation. Aktacir et al. (2010) conducted a case study on performance of building thermal insulation in Turkey in view of economy. Tosun & Dincer (2011) studied five different walls for their insulation performance with the application of artificial neural networks.

It could be concluded that previous researches on high reflectivity surfaces mainly focused on roof area, when it came to vertical wall area, reported studies were very limited (Joudi et al., 2011). Also previous researchers mainly focus on the effect of improving the reflectivity of roof surface, seldom studied the different effects of increasing roof reflectivity and thermal resistance. Studies on thermal insulation application in low latitude climate regions are limited and insulation installation for cold climates are aimed at reducing surface convection loss and the effects on vertical walls of different orientations are often overlooked justifiably. For cooling requirement dominating climate regions, thermal insulation and high reflectivity coating may have interchangeable functions, and yet they may produce savings of different magnitudes on walls of different orientations (Ozel, 2012). It also came to our attention that even for cold climate, the pros and cons of interior versus external insulation have not been well understood in relation to the climate and the occupancy pattern of the building.

2.1.3 Insulation against Window Glazing

As the most important fenestration style, windows play a very important part in providing thermal comfort and optimum illumination levels in buildings, and also a very important form in architectural area. Due to its relatively smaller U-value than wall area, the insulation of window area is an important topic in building energy research and management. In recent years, glazing technologies have received a significant adventure.

As early as 2000, Nielsen et al. (2000) presented a work of an easy method for determining the net energy gain through window area. The method took into consideration of orientation, shading and glazing material. Menzies & Wherrett (2005) conducted several survey studies to look into the sustainability and comfort issues of multi-glazed window. They claimed that during design of window area, the architects considered more about comfort. When it comes to sustainability, they did not consider much. Aydm (2000 & 2006) performed a numerical analysis on the heat transfer process in double pane windows using a finite difference technique. He discovered that for heat transfer through windows, there exist optimum thicknesses of air layer between glasses. Tian et al. (2010) developed a generalized window energy rating system for typical office building application and conducted a simulation study utilizing a typical Hong Kong office model. They claimed that their approach took both daylighting and thermal performance into consideration. They also claimed that their approach could be applied directly in area with similar climatic and geographic conditions to Hong Kong. Ochoa et al. (2012) conducted a simulation study tend to develop a design method for windows which took into consideration both low energy consumption and high visual comfort. They claimed that since the two aspects cannot be satisfied at the same time, necessary balance between different factors should be selected very carefully. They also discovered that choosing visual comfort criteria is more difficult. Tsikaloudaki et al. (2012) performed a simulation work in an ISO reference room to study the impact of different parameters on window performance in office buildings in Mediterranean zone. They discovered that solar transmittance played a more important role than thermal transmittance. They also discovered that if the solar transmittance is low, the fenestration would not be quite important.

Gasparella et al. (2011) developed a simulation work to study the impacts of glazing type, window size, orientation and internal heat gain to energy performance of residential building in four central and southern Europe cities. They found that the application of large glazing area could enhance winter performance. But in summer, shading system should be applied to avoid heat gain, south facing window performed best in winter. They also found that thermal transmittance appeared to be the most important factor that affects the performance of window. Singh & Garg (2009) collected the parameters of different window glazing in Indian market and conducted an energy rating. They tend to make a reference for designing buildings with different purpose and climate. Bojic et al. (2002) also investigated the performance of clear glazing, tinted glazing and reflective glazing in high-rise residential buildings and claimed that before assessing or retrofitting residential buildings, annual cooling load reduction, energy consumption and economic appraisal should be conducted beforehand. Poirazis et al. (2008) conducted a simulation work on energy performance of glazed office buildings in Sweden. They claimed that in order to keep the energy performance of full glazed single skin office building acceptable, a well-designed shading system is necessary. Wong et al. (2005) conducted a simulation study on energy and thermal comfort performance of double-glazed façade in Singapore. They claimed that due to the natural ventilation between two glazed layers, double layer façade could minimize energy consumption while enhance thermal comfort. They also claimed that during high humidity period, introduction of mechanical fans could solve the condensation problem. Smith et al. (2012) investigated a new retrofit measure which installed a secondary glazing on existing single-glazed window. They tested four different secondary glazing options and claimed that all four different glazing could significant reduce heat gain through window area, and the retrofit measure could considered to be a sound alternative for existing single-glazed window. Arici & Karabay (2010) calculated the optimum air layer thickness in four different climate zones in Turkey under heating condition. They claimed that the optimum thickness is between 12~15 mm. They also claimed that with application of a well-designed window, a saving of up to 60% could be achieved. Ismail et al. (2008 & 2009) conducted a simulation study to compare the thermal efficiencies of double layer glass window filled with absorbing gas exposed to solar radiation with both single layer glass window and double layer glass window naturally ventilated in hot climate. Three different mixtures of absorbing gas were simulated. They claimed that double layer glass window with absorbing gas and PCM performed better than regular double layer glass window naturally ventilated. Manz et al. (2006) investigated the impact of different parameters on the thermal performance of triple vacuum glazing through a simulation study. They suggested that even considering the effect of support pillar radius, separation and thermal conductivity, the performance of triple vacuum glazing is still better than other insulated glazing.

Chow et al. (2010) made a very detailed review on the state-of-art technologies of window glazing applied in cooling dominant climate. They introduced traditional single-glazed and double-glazed windows. They also paid much attention on newly developed water-flow window. Bojic & Yik (2007) investigated the application of low-e glazing to high-rise residential buildings in Hong Kong through a simulation work. They received a saving of 4% during the simulation and claimed that the application of expensive advanced glazing in residential building may not be economically viable in Hong Kong. They also found that the location of the target room within the building played a very important role. Assem & Al-Mumin (2010) utilized EnergyPlus software to simulate the glazing performance in fully glazed tall office building in Kuwait. They discovered that glazing heat gain is a major part in office building heat gain. In order to meet the government code, low-e glazing is necessary in government building, while in private building, some extra measure should also be applied. Fang et al. (2007) conducted a series of experimental and simulation study to test the thermal performance of low-e coating applied on vacuum glazing with a three-dimensional finite volume model. They claimed that while the emittance is small, the application of two coatings on glazing could only offer a very limited improvement in thermal performance. Under most circumstances, application of only one coating with vacuum glazing could already provide an excellent thermal performance.

Aldawoud (2013) modeled the performance of an electrochromic glazing system in hot dry climate and compared the result with traditional fixed shading device. He claimed that though higher cost, the electrochromic glazing could significantly reduce annual and peak cooling load compared with external shading device. Lee & Tavil (2007) also conducted a simulation work to assess the energy and visual performance of electrochromic windows with overhang. They tested performance of various combinations of overhang position and control strategies. They claimed that a reduction of 10% could be achieved in cold climate, and a reduction of 5% could be achieved in hot climate. They also claimed that performance of electrochromic glazing on moderate-area window is not that significant compared with large window. Dussault et al. (2012) conducted a simulation work to investigate a double-layer smart window with a controllable absorbing layer added on the interior surface of the exterior glass pane in Quebec City, Canada. They claimed that application of the smart window on south and west façades could receive a best performance, while application on north façade is not better than widely-applied low-e glass. Inoue et al. (2008) examined the performance of an autonomous responsive dimming glass through experiments and simulation. The dimming glass consisted of a transparent heating layer, an electrochromic layer and a polymer gel layer. They claimed that with appropriate control of the heating layer, the shading effects of the dimming glass are significant. Lu & Law (2013) investigated the overall energy performance of a single-glazed photovoltaic window in a typical Hong Kong office building through a simulation work. They took into consideration not only the heat gain reduction from solar radiation, but also the electricity generation as well as the daylighting performance. They claimed that the application of PV window could reduce around 65% of the total heat gain through window area, and an extra annual electricity of 900 to 1300 kWh could be expected. They also claimed that in the overall energy performance, the impact of thermal performance is the greatest, while the impact of daylighting performance is not significant. Chow et al. (2007 & 2009) also conducted a simulation work on the overall performance of PV ventilated window, they discovered that compared to conventional single glazing, a natural-ventilated PV window could reduce the space cooling load by about 28%. They also claimed that different orientations would receive a different energy performance, and a best performance could be received with a solar cell transmittance of 0.45 -0.55. Chow & Li (2013) also constructed a water-flow window to test its performance in practical building-like condition. They also built a mathematical model to simulate the annual energy performance. They claimed that a reduction of 8% could be achieved while compared to normal double-glazed window. Chow et al. (2006) tried to apply ventilation in double glazed window glazing. They also conducted a simulation study to research the impact of different configurations. Their finding indicated that in warm area like Hong Kong, a better energy performance could be achieved in summer with the application of ventilated window glazing. Jonsson & Roos (2010) tested the visual and energy performance of antireflection coating. They applied the coating on different types of glazing and simulated their performance. They discovered that in most cases, antireflection coating performed well, but when applied on low-e glazing, the antireflection coating did not make any impact.

Singh & Garg (2009) studied several different kinds of window glazing types applied in India, and discovered that the energy performance of window glazing is influenced by many factors such as thermal conductivity, solar heat gain coefficient, orientation of the window, climatic situation and building insulation as well as building shape. Fang et al. investigated the effect of glass thickness on the thermal performance of evacuated glazing in buildings, and claimed that considering the edge conduction, there existed an optimal glass thickness for a specific window glazing. Aydin (2000) studied the effects of air-layer thickness within the two layers of glass on the performance of the double-pane window under different climates, and discovered that there also existed optimum air-layer thickness for different climates.

Besides multiple layer window glass, other new glass materials are also playing important roles in modern building technologies. Low-e glass is short for low-emissivity glass. A low-e coating is applied on one of the surfaces of the traditional double glazing, which is a film mainly formed by dielectric and metal. The coating has a high transparency in the visible region and a high reflectance in the far-infrared region, which could provide a comfortable visual environment while making a good insulation effect. Thus low-e glass has a high transparency in the visible region and a high reflectance in the far-infrared region. Not only does it meet the requirement of buildings on good lighting, but it also prevents the far-infrared heat from passing through the coated glass (Huang et al., 2008). Finley (1999) studied the thermal performance of the low-e glass, and found that with the application of low-e glass, the heat loss through window area could be reduced by up to 70% during air-conditioning season. With the development of coating technology, it is very convenient for people to design the high transparency and high reflectance zones of the glass coating, thus the variety of low-e glass is increasing rapidly, and the function is getting more and more diversified. Low-e glass will no doubt become more important and common material in future building energy design area.

With the development of solar photovoltaic technology, building integrated photovoltaic system (BIPV) has drawn growing attention from building energy professionals. BIPV are photovoltaic materials which are used to replace conventional building materials in parts of the building envelope such as roofs and facades. By simultaneously serving as building envelope material and power generator, BIPV systems can provide savings in materials and electricity costs, reduce use of fossil fuels and emission of ozone depleting gases, and add architectural interest to the building. It is one of the most promising renewable energy technologies. Many parameters could affect the efficiency of the photovoltaic systems. Lu & Yang (2007) investigated the optimum tilt angle and orientation for BIPV systems, and discovered that in area such as Hong Kong, slopes exceeding 40 degree should be avoided, the yearly optimum tilt angle is about 20 degree, and if the slopes could be adjusted monthly, the energy performance could be much better. There were also lots of studies on life cycle performance of BIPV systems analysis (Lu & Yang, 2010; Keoleian & Lewis, 2003), but there are not many researches considering the shading effect of the BIPV system.

2.1.4 Shading Application on Windows

Research on performance of shading device began in about 1980s. Early reports did not pay much attention on quantitative analysis of shading performance. Methodical research started the last 15 years. Overhang could be considered to be the most traditional shading design in human's history. It is also the architects' favorite shading pattern. Raeissi & Taheri (1998) wrote a simulation program to calculate the hourly cooling load to determine the energy performance of overhang shading in Iran. They claimed that for a popular size house, overhang shading could reduce around 12%

cooling load in summer. Ebrahimpour & Maerefat (2011) conducted a simulation study on performance of advanced overhangs and glazing application in residential buildings in Iran. They tested several different combinations and received a detailed table of the most appropriate combinations for different orientations. Kim et al. (2012) discussed the thermal performance of different external shading devices that applied in residential apartments in South Korea in a simulation study. They claimed that a reduction of at least 11% in cooling load could be achieved by application of overhang. They also claimed that external blind could promise an at least 11% saving, while internal blind could save 10% energy at most. Cheng et al. (2013) did a deep research on variables that affect performance of overhang shading system, and proposed a methodical procedure to assess the performance of overhang shading in Taiwan. It should be admitted that though shading effect of overhang has been widely recognized, literature specially focused on overhang is very limited.

When it comes to blind, early research mainly focus on its daylighting performance As energy efficiency in building became a hot research issue, many researchers started to notice the energy performance of blinds. Clark et al. (2013) studied the convective heat transfer from window with venetian blinds. Results showed that the convective heat transfer is dependent on supply flow rate, blind angle, diffuse location as well as window configuration. Simmler & Binder (2008) conducted an experiment to test the total solar transmittance of glazing equipped with external blind. They believed that application of blind could significantly reduce solar transmittance of glazing. The color, tilt angle would affect the thermal performance of the blind shading system. Palmero-

Marrero & Oliveira (2010) calculated the indoor temperature with application of external louver blind. Different climate conditions were also taken into consideration. The simulation showed that application of louver blind on south façade could result in better thermal comfort. In climates with lower solar radiation and ambient temperature, the use of louver all year round may lead to a higher energy demand.

When green and sustainable building design became popular, automated control blind attracted much attention. The control strategies and the interaction between occupants and blind device were considered to be two important issues that affect the performance of blind significantly, which also drew much attention from researchers. Oh et al. (2012) conducted a simulation study on the lighting energy performance of automated blind in South Korea. Different control strategies had been considered during their simulation. According to their result, a reduction of 24.6% to 33.3% in lighting energy consumption could be expected with the application of automated blind. However, during their research, the cooling load caused by extra solar radiation was not taken into consideration. Olbina & Hu (2012) conducted a simulation study on daylighting and thermal performance of blinds. They claimed that manual blinds are often badly adjusted which make lighting, cooling and even heating loads increase. They proposed a new control method which splits the blind into several groups so that control moves could be made separately. They claimed that a better visual performance could be received at the back of the room. However, their research mostly focused on the daylighting performance, not much attention was paid on heat transfer side of blind. Hammad & Abu-Hijleh (2010) carried out a simulation study to examine the energy performance of dynamic external blind in office building in UAE. They achieved energy saving of 34%, 29% and 30% for south, east and west orientation respectively with the application of dynamic blind and lighting dimming system. Kim et al. (2009) as well as Koo et al. (2010) investigated the environmental performance of automated blind in South Korea. They designed an experiment involving an automated blind and a manual blind to compare their performance in energy saving as well as occupants' visual comfort. They claimed that considering the additional lighting energy consumption, a nearly equal energy performance could be achieved by employing automated blind or manual blind. After a very comprehensive and detailed literature review, Zhang & Barrett (2012) conducted a study on the occupants' blind-control behavior in office building. They claimed that occupants do not use blinds very often. They just set the blinds in certain positions based on long-term perceptions of sun light and sun heat. Changes of the sky condition within a day are often ignored. They also claimed that orientation and season would affect the occupants' control behavior, while air temperature, illuminance as well as solar radiation do not affect the blind control patterns much. Silva et al. (2012) carried out a simulation research to study the parameters that affect occupants' behavior towards blind shading control. They found that a large range of parameters could affect the occupants' control strategies, and different behavioral models result in different design alternative. They believed that a practical behavior model is necessary for building energy simulation. Wymelenberg (2012) reviewed over 50 relating researches on occupants' interaction with blind all around the world. He admitted that there is currently no widely accepted occupant control pattern for blind shading simulation. He also discovered that although automated blind is considered to be energy efficient, most occupants do not considered it well working.

2.2 Research on Daylighting Performance of Building Envelope

2.2.1 Introduction

Daylighting could be recognized as an important and effective approach in energy-efficient and green building development. Daylight is not only an excellent natural source of light, but also a connection between building inner space and outside world, which is recognized as an essential part in modern building design and construction. Daylighting performance of buildings has attracted the continuing attention of researchers' and designers'.

As early as 1991, the US government proposed a project named "Green Light Program", with the purpose to promote the development of efficient lighting and to control the lighting electricity. Policies such as fiscal subsidies and time-of-use price were also carried out. Since then, there had been an increasing interest in incorporating daylight in architectural and building design. It is believed that utilizing appropriate energy-efficient lamp as well as proper daylighting design, the energy consumption in buildings could be largely reduced, and the vision efficiency could also be improved at the same time (Li & Lam, 2001; Li et al., 2006).

Several models have been developed to calculate the illuminance from natural sources. CIE has done a great job on organization and summary of the calculation models, which make computer calculation and simulation of daylighting performance possible (CIE, 1973; CIE, 2003; Littlefair, 1992). The amount of daylight entering a building is mainly through window openings, and there are many factors that affect the indoor lighting environment, such as building area and orientation, the sky and sun condition, the size and position of the windows, the shading system, the depth and shape of the rooms, the colors of the internal surfaces.

2.2.2 Visual Performance of Daylighting System

While the windows serve as the main device of daylighting, direct sunlight through the window openings can cause the glare problem and the excessive contrast between the zone close to the window and that in the opposite end of the room. Furthermore, uncontrolled penetration of solar radiation can produce an extra load to air-conditioning systems. Application of shading system can help to achieve improved overall energy performance as well as enhanced lighting levels with visually comfortable uniformity. As early as 1990s, professionals had noticed the visual performance of building envelope. Yener (1999) developed a mathematical model for fixed shading system design considering both climate and visual comfort issues. He claimed that his model could help receive an optimum solution which minimize both air-conditioning and illumination energy consumption. However, daylighting effect was ignored in his research. Wienold and Christoffersen (2006) utilized a RADIANCE-based tool “evalglare” to evaluate several glare prediction models. They claimed that existing models have many uncertainties. With the help of CCD camera-based luminance mapping technology, they developed a new glare prediction equation. They also conducted a survey to collect data for their own developed model. Ochoa and Capeluto (2006) conducted a simulation study in Israel to investigate the performance of three different daylighting systems, namely a single layer window without any shading, a horizontal light shelf and a basic anidolic concentrator. They claimed that the anidolic concentrator could provide the highest daylight level. If glare protection was taken into consideration, a light shelf performed better. They suggested that in climate with high level of solar radiation, daylighting quality should be considered first. Hua et al. (2011) conducted a survey-based research to assess the dayliohgting performance in a laboratory building on a university campus. Through interview and measurement, they were able to get the occupants’ satisfaction towards the visual environment within the building. They also raised several suggestions on improvement of the indoor visual environment of the building. Lim et al. (2012) conducted a on-site measurement in a typical office building in Malaysia to test the daylighting performance of building envelope. They claimed that despite the external daylight level, the internal daylighting effect was always insufficient. They also claimed that application of light shelf could help improve the daylight distribution uniformity, but failed to reduce vertical glare. Besides, they found that simple modification of window glazing material and shading device could significantly improve the indoor visual comfort level. Konis (2013) examined the daylighting performance of an open-plan office building in San Francisco. He measured the electricity lighting energy consumption and conducted a survey on occupant modifications toward the building façade, so as to collect information on building daylighting performance. He discovered that visual discomfort is very common all over the workplace. In order to receive an acceptable visual environment, shading devices were necessary, even though daylight level in core zone dropped significantly. Ochoa & Capeluto (2006) investigated three different daylighting situations to evaluate their performances for deep office buildings in highly luminous climates, and discovered that if radiance level of outdoor light source is quite strong, application of proper shading devices could significantly improve the visual environment level, while single window could make the visual environment worse. Fernandes et al. (2013) conducted a simulation study to test the energy-saving potential of electrochromic windows daylighting system. The system was controlled by an auto-adjusted strategy with consideration of visual comfort. They claimed that an energy saving of about 40% could be expected with the application of electrochomic windows. Hirning et al. (2013) conducted a post-occupancy evaluation survey study on full-time employees in three green buildings in Brisbane to assess the glare related discomfort level in their working place. They discovered that nearly 60% of the respondents complained glare discomfort from both artificial and natural lighting. They also admitted that present evaluation models are not effective in glare prediction.

2.2.3 Energy Performance of Daylighting System

Li & Tsang (2008) as well as Aghemo et al. (2008) have carried out detailed studies on key building parameters affecting the daylighting designs, and found out that daylighting performance in office buildings as well as school buildings could be quite effective, in which situation about 25% of the total electric lighting energy consumption could be saved. It is also found that the scale of the room and the shading option could largely affect the daylighting performance of the buildings. These basic researches have laid a solid foundation for further investigations.

As the main source of daylight into the building, window openings provide the space near it a satisfying amount of daylight, while the rear part of the room cannot always get the demanding lighting. In order to fulfill the minimum requirement of visual environment, an artificial lighting system is needed. Early researches mainly focus on the simulation of energy saving from the artificial lighting dimming as a function of the daylighting availability. Bodart & Herde (2002) argued that only considering the amount of daylight that could be applied as light source, artificial lighting energy consumption could be reduced by 50%~80%. With the development of visual comfort research, studies have also been taken on the interaction and the energy-saving performance of daylighting and artificial lighting system. Li et al. (2006) had discovered that with the application of high frequency dimming control of daylighting equipment, the artificial lighting energy consumption could be reduced by more than 30%, they also discovered that utilizing energy-efficient light fitting with dimming control with proper daylighting schemes, the energy consumption could be further cut (Li et al., 2009).The performances of two basic categories of photoelectric lighting controls: the on-off control and the dimming control have also been discussed. It is believed that when it came to brightness of the working plane, the daylight availability is the key parameter to estimate the energy saving under on-off and dimming controls, as the daylight availability decreased, the dimming control acted efficiently, but when it was in a high level, the on-off control turned out to be better performing.

Reports on application of automated blind for energy conservation in buildings have increasingly appeared. Among these papers, performances of different shading system (the step-less control and the 5-position designated control) have been investigated, Galasiu & Atif (2004) studied the interaction of step-less controlled window blinds and automatic on/off controlled artificial lighting system, and argued that although application of daylighting could reduce 50%~60% of lighting consumption in the building, the automatic controlled shading system would largely reduce the energy saving effect. Athienitis & Tzempelikos (2002) studied a double-glazed window with motorized highly reflective blinds between the two glazes, and claimed that the energy saving due to the system could be up to 70%~90%. Chaiwiwatworakul et al. (2009) investigated automatic controlled horizontal blinds in Thailand, with a step-less control strategy, and found an energy saving of up to 80%. Lee & Selkowitz (2006) monitored a 5-position controlled window blinds in New York City, and discovered that under the 5-position control strategy, the energy saving could still be as high as nearly 60%. Control strategies based on different parameters have also been studied. Moeseke et al. (2007) studied the impacts of internal temperature and solar irradiation on the efficiency of shading devices, and discovered that temperature set point had little influence on the energy consumption. Kim et al. (2009) studied the impact of outdoor weather condition on the performance of shading system, and they claimed that the performance of shading device would be largely affected by outdoor weather, and the strategy should be arranged considering indoor situation. The energy-saving results of each study have been simulated and calculated, and the performances have been discussed. Some advanced materials and devices have also been mentioned as solutions to thermal and visual comfort and energy conservation. Inoue (2003) investigated the performance of autonomous response dimming glass on the window, and claimed that the glass could significantly improve the energy and daylighting performance of the buildings, and had been considered by most occupants. Li et al. (2004) studied the lighting and energy performance of solar film coating in office buildings, and they found a 30% decline in solar radiation heat gain. Ghisia & Tinker (2006) studied the potential for energy saving on lighting by fiber optics in different countries of the world, and reported an energy saving of ranging from 8% to 92%. Mehlika et al. (2005) also studied the performance of semi-transparent solar cell window, and claimed that there existed an ideal percentage of semi-transparent solar cell windows for different climate. All the above results showed that with proper design and control strategy, the shading devices could significantly reduce the energy consumption in buildings and supply a not only visually but also thermally more comfortable environment within buildings.

Recently, with the development of building energy simulation software, researchers could easily simulate the performance of different daylighting devices and the effects of different factors on energy and visual performance. The ideal window size, direction and types to minimize energy consumption of buildings have been studied by Mehlika et al. (2000). The performance of the interaction of shading devices and artificial lighting system is also studied through building energy simulation by Sullivan et al. (1992), and they reported that the simulation result was quite closed to experimental data from their previous researches. Through large number of case simulations, the effect of indoor temperature setting point on the daylighting performance of windows has been studied by Kontoleon & Bikas (2002), and they claimed that the glazed opening percentages had a huge effect on thermal performance of the buildings. Al-Homound (1997) also simulated the daylighting performance under different climate situation and made interesting analysis with other experimental studies. Energy savings due to daylighting application on buildings has been investigated by a combination of daylighting simulation and a dynamic thermal simulation by Bodart & De Herde (2002). Moreover, Johnson et al. (1990) simulated the economically optimum window area and direction has also been studied through software simulation. With the support of detailed data, researchers could even evaluate the performance of advanced shading or window materials (Miyazaki et al., 2005).

2.3 Summary of Literature Review and Objective of the Thesis

2.3.1. Summary of Literature Review

In visual performance aspect, daylighting performance of window glazing and shading device has been investigated. The indoor daylighting illumination level and distribution under different devices and control strategies has also been studied. The energy saving from artificial lighting system under different daylighting devices and control strategies has been discussed. However, daylight is always coupled with solar radiation. Daylighting application will always bring in solar radiation heat gain for building inner space, which would become cooling load for air-conditioning system eventually. These two conflict factors make it complicated to achieve an optimum design for transparent surface of building envelope. There are few literatures on this issue in existing studies.

In thermal performance aspect, existing literatures could be divided into two parts: studies on wall area and studies on window area. For wall-related researches, previous studies on high reflectivity surfaces mainly focused on roof area, when it came to vertical wall area, reports were very limited. Also previous researchers mainly focus on the effect of improving the reflectivity of roof surface, seldom studied the different effects of increasing roof reflectivity or thermal resistance. Studies on thermal insulation application in low latitude climate regions are limited. Insulation for cold climates is aimed at reducing surface convection loss and the effects on vertical walls of different orientations are often overlooked justifiably. For window area, there have been several studies on energy performance of blind and overhang shading systems. Key variables that affect the performance have also been investigated. But most studies focus on residential building, research on commercial building is limited. Current studies tend to consider the building envelope as a whole, the impact of orientation is often ignored. Majority of reports focus on simulation or experiment on one single local building, the impacts of geography location are not discussed. Besides, though there have been many studies on automated blinds, its performance is not stable and its application is not widely acceptable. In most cases, designers still prefer conventional blind devices.

Lighting and air-conditioning are among the top components in building energy consumption. To achieve a satisfactory building energy management, professionals should take both visual and thermal performances into consideration. The objection of this thesis is to investigate the thermal and visual performance of building envelope in cooling-dominant climates. Assessments will be given considering their comprehensive performances, so that a more exhaustive evaluation for different envelope devices could be achieved, which could serve as useful reference for engineers and research professionals.

2.3.2. Research Objective

The overall objective of this study is to conduct a detailed comprehensive evaluation on the energy performance of commonly used insulation and shading measures in cooling dominant climates. The evaluation takes into consideration not only the thermal performance, but also the daylighting performance. The results can serve as a reference for practical building retrofitting as well as designing.

The first objective of this study is to evaluate the thermal performance of different energy-efficient designs on windows. In cooling-dominant climates a typical window is a single-layer glass with certain type of shading. A series of simulation studies were conducted to investigate the impact of glazing property such as glass thickness, air layer thickness in double-layer glass as well as solar transmittance of low-e coating. Other parameters such as orientation, building function and geography location were also examined. The study also investigated the heat gain reduction from the two most popular shading devices, namely the external overhang and the interior blind. Simulation studies were carried out to investigate the impact of material property on the shading device's thermal performance. For the interior blind, occupants' behaviour could significantly affect its performance, which was also investigated in this study.

The second objective of this research is to assess the daylighting performance of all these window designs in cooling-dominant climates. A series of simulation studies were conducted to calculate the lighting energy saving under different glazing materials and shading devices. Energy saved from the lighting system due to the application of daylighting strategy was achieved, through which the daylighting performance of different alterations can be assessed. The impact of orientation as well as geography location were also considered and discussed.

The third objective of this study is to evaluate the thermal performance of insulation alterations on building external walls. Insulation against envelope walls is generally applied in high-latitude cold climates. This study tried to discuss its applicability in low-latitude, cooling-dominant regions. The two most commonly applied approaches, namely thermal insulation and high-reflectivity coating were selected. A series of simulation studies were conducted to calculate the proposed alterations' effects on both the annual cooling load and the peak cooling load. Different parameters such as orientation, geography location, building function and installation position (internal versus external) which affect the performance were discussed in detail.

Chapter 3

Research Methodology

3.1 Introduction

In this Chapter, the investigation methods applied in this study are described. The important issues of each research methods are outlined. The overall objective of this study is to conduct a detailed evaluation on the overall performance of commonly applied building envelope designs on commercial building envelope in cooling dominant climates. In order to receive a comprehensive evaluation result, both thermal and daylighting performance will be discussed during the study. Two kinds of world famous building energy simulation software, namely EnergyPlus and Daysim are applied during simulation study.

EnergyPlus is a whole building energy simulation program which is developed by the Lawrence Berkeley National laboratory Simulation Research Group, the Building Systems Laboratory at the University of Illinois, the Florida Solar Energy Center, National Renewable Energy Laboratory, and the U.S. Department of Energy. Based on state-space techniques, EnergyPlus is able to calculate the space load required to maintain a set condition through some sort of HVAC system. Many previous studies have proved its accuracy and adaptability (Zhou et al., 2008; Tabares-Velasco et al., 2012; Henninger et al., 2004).

Daysim is a dynamic RADIANCE-based daylighting simulation program that calculates the annual daylight amount received with in buildings. Daysim allows users to calculate the annual electric lighting energy consumption under certain illumination level set-point. Daysim could be directly coupled with thermal simulation program such as EnergyPlus so that a comprehensive building energy analysis could be received (Yun & Kim, 2013; Jakubiec & Reinhart, 2013).

3.2 EnergyPlus Simulation Principle

The simulation in EnergyPlus is an integrated procedure in which all major components are simulated simultaneously. The core of EnergyPlus simulation process is fundamental heat balance principle. The zone and air system integration is based on the heat and moisture balances on the zone air:

$$C_{zone}\frac{dT}{dt}=\sum_{i=1}^{n}Q_i+\sum_{i=1}^{n_{surfaces}}h_iA_i\left(T_{isurface}-T_{zone}\right)+\sum_{i=1}^{n_{zone}}m_iC_p\left(T_{izone}-T_{zone}\right)+m_{\inf}C_p\left(T_{en}-T_{zone}\right)+Q_{sys} \quad (3.1)$$

Where $C_{zone}\frac{dT}{dt}$ stands for internal energy change on zone air. Q_i stands for convective internal load caused by internal heat source. $h_iA_i\left(T_{isurface}-T_{zone}\right)$ stands for the convective heat transfer through the zone surface i. $m_iC_p\left(T_{izone}-T_{zone}\right)$ stands for the heat transfer due to the air mixing from the zone i. $m_{\inf} C_p \left(T_{en} - T_{zone}\right)$ stands for the heat transfer caused by infiltration of outdoor air. Q_{sys} stands for the energy provided to the zone by air-conditioning system.

3.2.1 Finite Difference Approach Used during Simulation

In order to calculate the derivative of zone air temperature to time, a finite difference approach should be used. There are three different solution algorithms to solve the zone heat and moisture balance equation in EnergyPlus. They are defined as 3rdOrderBackwardDifference method, Euler method and AnalyticalSolution method, respectively. In the following simulation research, 3rdOrderBackwardDifference method is applied as the solution algorithm. The main difference between the 3rdOrderBackwardDifference method and the other two methods is the order of the finite difference derivative. The 3rdOrderBackwardDifference method involves the third order finite difference approximation, while the other two methods use first order finite difference approximation. The application of higher order difference derivative is to avoid instabilities when time step size is large. According to the research of Taylor et al. (1990), the third order finite difference approximation could give a best result:

$$\frac{dT_{zone}}{dt} = \frac{\frac{11}{6}T_{zone}^{t} - 3T_{zone}^{t-\delta t} + \frac{3}{2}T_{zone}^{t-2\delta t} - \frac{1}{3}T_{zone}^{t-3\delta t}}{\delta t} + O\left(\delta t^{3}\right) \tag{3.2}$$

Applying formula 3.3 to formula 3.1:

$$\frac{C_{zone}\left(\frac{11}{6}T_{zone}^{t}-3T_{zone}^{t-\delta t}+\frac{3}{2}T_{zone}^{t-2\delta t}-\frac{1}{3}T_{zone}^{t-3\delta t}\right)}{\delta t}=\sum_{i=1}^{n}Q_i+\sum_{i=1}^{n_{surfaces}}h_iA_i\left(T_{isurface}-T_{zone}\right)+\sum_{i=1}^{n_{zone}}m_iC_p\left(T_{izone}-T_{zone}\right)+m_{\inf}C_p\left(T_{en}-T_{zone}\right)+Q_{sys} \tag{3.3}$$

$$T_{zone}^{t}=\frac{\sum_{i=1}^{n}Q_i+\sum_{i=1}^{n_{surfaces}}h_iA_iT_{isurface}+\sum_{i=1}^{n_{zone}}m_iC_pT_{izone}+m_{\inf}C_pT_{en}+m_{sys}C_pT_{\sup ply}-\frac{C_{zone}}{\delta t}\left(-3T_{zone}^{t-\delta t}+\frac{3}{2}T_{zone}^{t-2\delta t}-\frac{1}{3}T_{zone}^{t-3\delta t}\right)}{\frac{11}{6}\frac{C_{zone}}{\delta t}+\sum_{i=1}^{n_{surfaces}}h_iA_i+\sum_{i=1}^{n_{zone}}m_iC_p+m_{\inf}C_p+m_{sys}C_p} \tag{3.4}$$

If the purpose of the simulation process is to calculate the space cooling load under certain space temperature set point, a steady state should be reached, which means $dT_{zone}/dt=0$. Put Q_{sys} alone to one side of the equation. In a steady-state situation, the energy provided by the air-conditioning system should be:

$$-Q_{sys}=\sum_{i=1}^{n}Q_i+\sum_{i=1}^{n_{surfaces}}h_iA_i\left(T_{isurface}-T_{zone}\right)+\sum_{i=1}^{n_{zone}}m_iC_p\left(T_{izone}-T_{zone}\right)+m_{\inf}C_p\left(T_{en}-T_{zone}\right) \tag{3.5}$$

3.2.2 Heat Gain through Wall Surface

The basic principle for conduction heat gain through a surface is the response factor method:

$$q^{"}(t) = \sum_{j=0}^{\infty} X_j T_{out}^{t-j\delta} - \sum_{j=0}^{\infty} Y_j T_{in}^{t-j\delta} \tag{3.6}$$

Where $q^{"}(t)$ stands for heat flux through a surface. T_{out} stands for temperature outside the building. T_{in} stands for temperature inside the building. X_j and Y_j are response factors. In EnergyPlus, conduction transfer functions (CTF) are applied to reduce errors caused by inaccurate response factors:

$$q_{in}^{"}(t) = -Z_0 T_{in}^{t} - \sum_{j=1}^{nz} Z_j T_{in}^{t-j\delta} + Y_0 T_{out}^{t} + \sum_{j=1}^{nz} Y_j T_{out}^{t-j\delta} + \sum_{j=1}^{nz} \Phi_j q_{in}^{"t-j\delta} \tag{3.7}$$

$$q_{out}^{"}(t) = -Y_0 T_{in}^{t} - \sum_{j=1}^{nz} Y_j T_{in}^{t-j\delta} + X_0 T_{out}^{t} + \sum_{j=1}^{nz} X_j T_{out}^{t-j\delta} + \sum_{j=1}^{nz} \Phi_j q_{out}^{"t-j\delta} \tag{3.8}$$

Where $q_{in}^{"}(t)$ stands for conduction heat flux on inside surface. $q_{out}^{"}(t)$ stands for conduction heat flux on outside surface. X , Y and Z are outside surface CTF coefficient, cross surface CTF coefficient and inside surface CTF coefficient, respectively. Φ stands for flux CTF coefficient. From above equation it is clear that heat flux at a wall surface is linearly related to current and several previous surface temperatures and several previous inside surface heat flux value. A linear equation and constant CTF coefficients make the calculation of conduction heat transfer simple (USDOE, 2011).

In EnergyPlus, the state space method is used to calculate the conduction transfer functions (Ouyang and Haghighat, 1991). The basic definition of state space method is expressed below:

$$\frac{d[T_n]}{dt} = [A][T_n] + [B]\begin{bmatrix} T_{in} \\ T_{out} \end{bmatrix} \tag{3.9}$$

$$\begin{bmatrix} q''_{in} \\ q''_{out} \end{bmatrix} = [C][T_n] + [D]\begin{bmatrix} T_{in} \\ T_{out} \end{bmatrix} \tag{3.10}$$

Where $[T_n]$ stands for $[T_1, T_2 ... T_n]^T$ which is a description of state, $\begin{bmatrix} T_{in} \\ T_{out} \end{bmatrix}$ is the input vector, $\begin{bmatrix} q''_{in} \\ q''_{out} \end{bmatrix}$ is the output vector. $[A]$, $[B]$, $[C]$ and $[D]$ are coefficient matrixes.

For a wall element, the heat balance on the outside surface should be (USDOE, 2011):

$$q''_{asol} + q''_{LWR} + q''_{conv} + q''_{out} = 0 \tag{3.11}$$

Where q''_{asol} stands for the absorbed direct and diffuse short wavedepth solar radiation heat flux. q''_{LWR} stands for the long wavedepth radiation heat exchange between the surface and surroundings. q''_{conv} stands for the convective heat exchange between the surface and air. The calculations of these values are presented below:

$$q''_{asol} = \alpha\left(I_b \cos\theta \frac{A_s}{A} + I_s F_{ss} + I_g F_{sg}\right) \tag{3.12}$$

$$q''_{LWR} = \varepsilon\sigma F_{ground}\left(T^4_{ground} - T^4_{out}\right) + \varepsilon\sigma F_{sky}\left(T^4_{sky} - T^4_{out}\right)\varepsilon\sigma F_{air}\left(T^4_{air} - T^4_{out}\right) \tag{3.13}$$

$$q''_{conv} = h_{out} A\left(T_{out} - T_{air}\right) \tag{3.14}$$

Where α stands for the solar absorptance of the surface, I_b stands for the intensity of beam solar radiation, I_s stands for the intensity of sky diffuse radiation, I_g stands for the intensity of ground diffuse radiation, θ is the angle of incidence of beam solar radiation. A_s stands for the sunlit area. A stands for the surface area. F_{ss} is the angle factor between the surface and the sky. F_{sg} is the angle factor between the surface and the ground. ε stands for the long wave emittance of the surface. σ is Stefan-Boltzmann constant. F_{ground}, F_{sky} and F_{air} are the view factors of surface to ground, sky and air, respectively. T_{ground}, T_{sky} and T_{air} are the temperatures of ground, sky and air, respectively. h_{out} stands for the outside surface convective coefficient.

For a wall element, the heat balance on the inside surface should be (USDOE, 2011):

$$q^{"}_{LWZ} + q^{"}_{SW} + q^{"}_{LWE} + q^{"}_{in} + q^{"}_{conv} = 0 \tag{3.15}$$

Where $q^{"}_{LWZ}$ stands for the long wavedepth radiation heat exchange between zone surfaces. $q^{"}_{SW}$ stands for the short wavedepth radiation heat exchange between surface and lights. $q^{"}_{LWE}$ stands for the long wavedepth radiation heat exchange between surface and equipment. $q^{"}_{conv}$ stands for the convective heat exchange between the surface and air. $q^{"}_{conv}$ is considered to be the immediate space cooling load. For radiation heat exchange calculation, the equation below could be applied:

$$q_j = AF_j \left(T_{in}^4 - T_j^4 \right) \tag{3.16}$$

Where q_j stands for radiation heat exchange between the wall surface and other wall surfaces/lights/equipment. F_j stands for view factors between the wall surface and other wall surfaces/lights/equipment. T_j stands for surface temperatures of other wall surfaces/lights/equipment.

3.2.3 Heat Gain through Window Surface

During the calculation of window heat balance equations, EnergyPlus makes several assumptions to simplify the process (USDOE, 2011):

1. The glazing layer is thin enough that heat storage in the glazing can be neglected.

2. The heat flow is one dimensional (perpendicular to the glazing surface).

3. The glazing layer is opaque.

4. The glazing surface is isothermal.

5. The Short wave radiation absorbed by a glazing layer can be apportioned equally to the two surface of the layer.

The heat balance equations of window are quite similar to those of wall. For each glazing layer, there are two surfaces and therefore two equations:

$$E_{out}\varepsilon_{out} - \varepsilon_{out}\sigma T_{out}^4 + k\left(T_{in} - T_{out}\right) + h_{out}\left(T_{air} - T_{out}\right) + S_{out} = 0 \tag{3.17}$$

$$E_{in}\varepsilon_{in} - \varepsilon_{in}\sigma T_{in}^4 + k\left(T_{out} - T_{in}\right) + h_{in}\left(T_{space} - T_{in}\right) + S_{in} = 0 \tag{3.18}$$

Where E_{out} and E_{in} stand for exterior and interior long wave radiation incident on glazing surface. ε_{out} and ε_{in} are emissivity of outside and inside surfaces. T_{out} and T_{in} are temperatures of outside and inside surface. S_{out} and S_{in} are radiation heat absorbed by outside and inside surfaces. k stands for the conductance of glazing layer. h_{out} and h_{in} are convective coefficients of outside and inside surface. T_{air} stands for temperature of outside air. T_{space} stands for temperature of inside air.

According to assumptions above, the short wave radiation absorbed by a glazing layer is split equally to the two surface of the layer. Therefore absorbed radiation heat is calculated as:

$$S_{out} = S_{in} = \frac{1}{2}\left(I_{bm}^{ex}\cos\varphi A_f^{bm}\varphi + I_{dif}^{ex}A_f^{dif} + I_{sw}^{\mathrm{int}}A_b^{dif}\right) \tag{3.19}$$

Where I_{bm}^{ex} stands for the exterior beam normal solar irradiance. I_{dif}^{ex} stands for exterior diffuse solar incident on glazing from outside. I_{sw}^{int} stands for interior short wave radiation incident on glazing from inside. A_f^{bm} stands for front beam solar absorptance of glazing layer. A_f^{dif} and A_b^{dif} are front and back diffuse solar absorptance of glazing layer.

Besides simple glazing, shading device is also an important component of window system. Well-designed shading system could reduce unwanted radiation heat gain through window area, therefore is widely used in buildings all over the world. In EnergyPlus, taking interior shading device for example, the heat balance equation for the glazing surface facing the shading device and the shading surface facing the glazing are (USDOE, 2011):

$$\frac{E_{in}\varepsilon_{in}\tau_{sh}}{1-\rho_{in}\rho_{sh}}+\frac{\sigma\varepsilon_{in}}{1-\rho_{in}\rho_{sh}}\left[\varepsilon_{sh}T_{sh}^4-\left(1-\rho_{sh}\right)T_{in}^4\right]+k\left(T_{out}-T_{in}\right)+h_{in}\left(T_{gap}-T_{in}\right)+S_{in}=0 \tag{3.20}$$

$$\frac{E_{in}\varepsilon_{sh}\rho_{in}\tau_{sh}}{1-\rho_{in}\rho_{sh}}+\frac{\sigma\varepsilon_{sh}}{1-\rho_{in}\rho_{sh}}\left[\varepsilon_{in}T_{in}^4-\left(1-\rho_{in}\left(\varepsilon_{sh}+\rho_{sh}\right)\right)T_{sh}^4\right]+k_{sh}\left(T_{shin}-T_{sh}\right)+h_{in}\left(T_{gap}-T_{sh}\right)+S_{in}=0 \tag{3.21}$$

Where τ_{sh} stands for the IR diffuse transmittance of the shading device. ε_{sh} stands for the diffuse emissivity of the shading device. ρ_{in} stands for the IR diffuse reflectance of the glazing surface. ρ_{sh} stands for the IR diffuse reflectance of the shading device surface. T_{sh} stands for the surface temperature of the shading device facing glazing. T_{gap} stands for the effective mean air temperature of the air layer between glazing and shading device. T_{shin} is the temperature of the shading device surface facing indoor.

From formula 3.20 and 3.21 it is clear that convective heat transfer between element surface and the air gap is an important feature in the calculation of shading device heat balance. The core problem lies in the solution of T_{gap} and h_{in}. In EnergyPlus, the convective heat transfer coefficient between element surface and the air gap is given by (USDOE, 2011):

$$h_{in} = 2h_c + 4v \tag{3.22}$$

Where h_c stands for the surface-to-surface heat transfer coefficient for non-vented cavity. v stands for the mean air velocity in the air gap. In order to calculate T_{gap} and v, a pressure balance equation for airflow in the gap is necessary:

$$\Delta p_d = \Delta p_B + \Delta p_{HP} + \Delta p_Z \tag{3.23}$$

Where Δp_d is the driving pressure difference between space air and gap air. Δp_B is the dynamic pressure due to airflow. Δp_{HP} stands for the pressure drop caused by shading and glazing surface. Δp_Z stands for the pressure drop due to the inlet and outlet of the air gap. The calculations of the above terms are given below:

$$\Delta p_d = \rho_0 T_0 g H \sin\phi \frac{\left|T_{gap} - T_{space}\right|}{T_{gap} T_{space}} \tag{3.24}$$

$$\Delta p_B = \frac{\rho_{gap}}{2} v \tag{3.25}$$

$$\Delta p_{HP} = 12 \mu_{gap} \frac{H}{s^2} v \tag{3.26}$$

$$\Delta p_Z = \frac{\rho_{gap} v^2}{2} \left[\left(\frac{sH}{0.66 A_{in}} - 1 \right)^2 + \left(\frac{sH}{0.60 A_{out}} - 1 \right)^2 \right] \tag{3.27}$$

Where ρ_0 and T_0 stand for the air density and temperature at 283K. H stands for the height of the shading device. ϕ is the tilt angle of the window. ρ_{gap} and μ_{gap} stand for the air density and viscosity at T_{gap}. s stands for the thickness of the air gap. A_{in} and A_{out} stand for the equivalent inlet and outlet opening area of the air gap. Solving equation 3.23 to 3.27, v is given by:

$$v = \frac{\left[\left(12\mu\frac{H}{s^2}\right)^2 + \frac{2\rho_{gap}^2\rho_0 T_0 H\sin\phi\left[1+\left(\frac{A_{gap}}{0.66A_{in}}-1\right)^2+\left(\frac{A_{gap}}{0.60A_{out}}-1\right)^2\right]\left|T_{gap}-T_{space}\right|}{T_{gap}T_{space}}\right]^{0.5} - 12\mu\frac{H}{s^2}}{\rho_{gap}\left[1+\left(\frac{A_{gap}}{0.66A_{in}}-1\right)^2+\left(\frac{A_{gap}}{0.60A_{out}}-1\right)^2\right]} \tag{3.28}$$

The expression of T_{gap} is given by:

$$T_{gap} = \frac{T_{in}+T_{sh}}{2} - \frac{\rho_{gap}C_p s v}{2h_{in}H}\left(\frac{T_{in}+T_{sh}}{2} - \left(\frac{T_{in}+T_{sh}}{2} - T_{space}\right)e^{-\frac{2h_{in}H}{\rho_{gap}C_p s v}}\right) \tag{3.29}$$

3.3 Daysim Simulation Principles

In the simulation process, Daysim combines reverse ray tracking algorithm and daylight coefficient together, therefore significantly reduces time cost for annual dynamic simulation. The following section will introduce the basic algorithm used in Daysim calculation. Figure 3.1 shows a schematic of CIE standard sky model (CIE, 1973). Angles appearing in the models are also given in Figure 3.1.

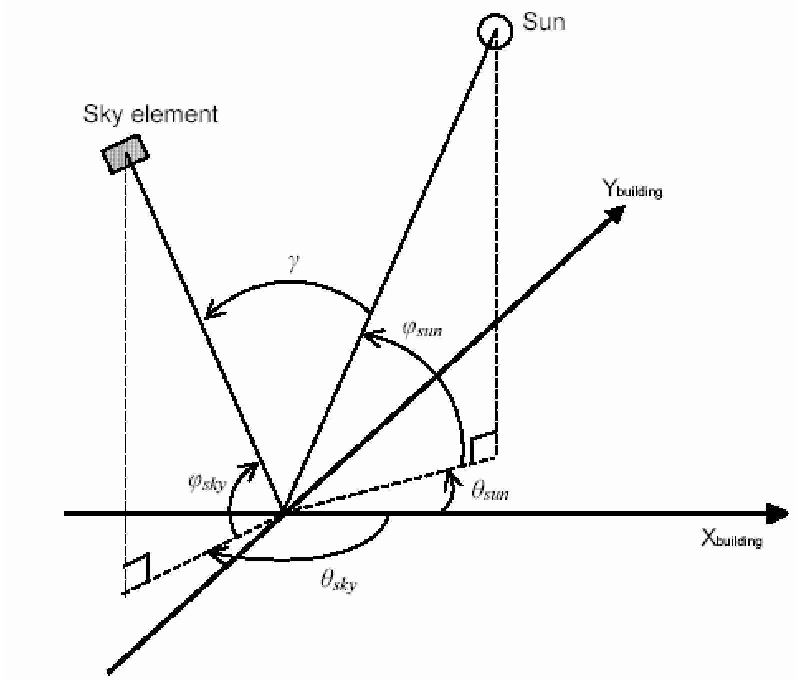


Figure 3. 1 Schematic of CIE standard sky model

Clear sky luminance distribution is given by:

$$\psi_{cs}(\theta_{sky},\phi_{sky}) = L_z \frac{(0.91+10e^{-3\gamma}+0.45\cos^2\gamma)(1-e^{-0.32\operatorname{cosec}\phi_{sky}})}{0.27385(0.91+10e^{-3(\frac{\pi}{2}-\phi_{sun})}+0.45\sin^2\phi_{sun})} \tag{3.30}$$

Clear turbid sky luminance distribution is given by:

$$\psi_{ts}(\theta_{sky},\phi_{sky}) = L_z \frac{(0.856+16e^{-3\gamma}+0.3\cos^2\gamma)(1-e^{0.32\operatorname{cosec}\phi_{sky}})}{0.27385(0.856+10e^{-3(\frac{\pi}{2}-\phi_{sun})}+0.3\sin^2\phi_{sun})} \tag{3.31}$$

Intermediate sky luminance distribution is given by:

$$\psi_{ts}(\theta_{sky},\phi_{sky}) = L_z Z_1 Z_2 /(Z_3 Z_4) \tag{3.32}$$

$$Z_1 = [1.35(\sin(3.59\phi_{sky}-0.009)+2.31)\sin(2.6\phi_{sun}+0.316)+\phi_{sky}+4.799]/2.326 \tag{3.33}$$

$$Z_2 = \exp[-0.563\gamma\{(\phi_{sun}-0.008)(\phi_{sky}+1.059)+0.812\}] \tag{3.34}$$

$$Z_3 = 0.99224\sin(2.6\phi_{sun}+0.316)+2.73852 \tag{3.35}$$

$$Z_4 = \exp[-0.563(\frac{\pi}{2}-\phi_{sun})\{2.6298(\phi_{sun}-0.008)+0.812\}] \tag{3.36}$$

Overcast sky luminance distribution is given by:

$$\psi_{os}(\phi_{sky}) = L_z \frac{1+2\sin\phi_{sky}}{3} \tag{3.37}$$

Where L_z stands for the zenith luminance. In the calculation of daylight factor, L_z equals to 1.0 in all sky models. With the selection of appropriate sky model, the sky background luminance could be calculated. During the indoor lighting calculation, consider the illumination at a specified point to be $\mathrm{E_P}$:

$$\mathrm{E_P} = \mathrm{E_S} + \mathrm{E_{SE}} + \mathrm{E_{ERE}} + \mathrm{E_{IRE}} \tag{3.38}$$

Where $\mathrm{E_S}$ is the illumination from direct solar radiation. $\mathrm{E_{SE}}$ stands for the illumination from sky. $\mathrm{E_{ERE}}$ stands for the illumination reflected from surrounding environment. $\mathrm{E_{IRE}}$ stands for the illumination reflected from indoor.

The expression of $\mathrm{E_S}$ is given by:

$$\mathrm{E_S} = \mathrm{E_{D,surf}}\, 1.018\, \mathrm{T_g} \cos\phi_{sun}\left(1+\sin^3\phi_{sun}\right)\mathrm{D_g F_g} \tag{3.39}$$

Where $E_{D,surf}$ is the solar illumination on the surface. T_g stands for the transmittance of the glazing. D_g stands for the dust coefficient of the glazing. F_g stands for the structure coefficient of the glazing.

The expression of E_{SE} is given by:

$$E_{SE} = E_a T_g C \tag{3.40}$$

Where E_a stands for the illumination on the external surface of glazing. C stands for the flux transfer structure factor.

The expression of E_{ERE} is given by:

$$E_{ERE} = [(E_s \rho_s T_g) + (E_S \rho_S T_g)]C \tag{3.41}$$

Where E_s stands for the illuminance of the surface that reflects sky illumination. E_S stands for the illuminance of the surface that reflects solar direct illumination.

The expression of C is given by:

$$C = \frac{1}{2\pi} \sum_{i=1}^{2} \sum_{j=1}^{2} F[(x_i, y_j)(-1)]^{i+j} \tag{3.42}$$

$$F(x,y) = \frac{x}{\sqrt{x^2+z^2}} \arctan \frac{y}{\sqrt{x^2+z^2}} + \frac{y}{\sqrt{y^2+z^2}} \arctan \frac{x}{\sqrt{y^2+z^2}} \quad \text{(For vertical surface)} \tag{3.43}$$

$$C = \frac{z}{2\pi} \sum_{i=1}^{2} \sum_{j=1}^{2} F[(x_i, y_j)(-1)]^{i+j} \tag{3.44}$$

$$F(x,y) = \frac{-1}{\sqrt{x^2+z^2}} \arctan \frac{y}{\sqrt{x^2+z^2}} \quad \text{(For horizontal surface)} \tag{3.45}$$

The expression of E_{IRE} is given by:

$$E_{IRE} = \frac{\left(\sum_{i=1}^{n} E_i A_i \rho_i + \sum E_s A_s \rho_s \right)}{(1-\rho_{avg}) A_r} \tag{3.46}$$

Where E_i, A_i and ρ_i stand for the centroid illumination, area and reflectivity of each wall surface. E_s, A_s and ρ_s stand for the centroid illumination, area and reflectivity of each surface that receives direct solar radiation. ρ_{avg} stands for the average reflectivity within the space. A_r stands for the total area within the space.

3.4 On-site Measurement on Interior Blind Performance

3.4.1 Introduction

In order to get a direct perception on the performance of energy-efficient designs, an on-site measurement is also arranged. An east facing air-conditioned single office equipped with interior blind on the university campus is selected for the measurement. Figure 3.2 presents the layout of the office room.

The selected office room is surrounded by air-conditioned area, which ensures that no heat transfer occurs on internal wall area. The space cooling load within the office is monitored by energy balance calculation.

Figure 3. 2 Layout of the office room and air-conditioning system

The space cooling load within the office is handled by a conventional fan coil unit. During the monitor period the office is un-occupied. All office appliances are switched off. No internal loads are presented. According to heat balance inside the office, the enthalpy difference between supply and exhaust air would be the space cooling load during monitor period. Since no heat transfer occurs on internal wall surface, it can be considered that the majority of space cooling load within the office is caused by heat gain through external wall area.

3.4.2 Measurement Method

For enthalpy measurement, HOBO data loggers are selected to measure the air temperature (±0.4℃) and relative humidity (±2.5%). A SERIES 8400 “FLOW HOOD” backpressure compensated air balance system (±3%) manufactured by shortridge instruments Inc. is selected to measure the air flow rate, as presented in Figure 3.3.

Figure 3. 3 Measurement of air flow rate

Five measuring points are selected in the office. The temperature and relative humidity at air supply unit, air return unit, working desk, beside the window and beside the door is monitored. The recording time step is set at 5 min.

During the monitor period, according to heat balance inside the office, the enthalpy difference between supply and return air is considered to be the instantaneous space cooling load. The air temperature and air humidity of supply and return air are recorded every 5min. Formula 3.47 to 3.51 give the enthalpy calculation method from the data. t (℃) stands for air temperature, d (g/kg dry air) stands for air humidity. B (Pa) stands for the local pressure. P_q (Pa) stands for saturated vapour pressure. φ stands for relative humidity. Formula 3.50 gives the calculation method of air density under different temperature. Formula 3.51 gives the calculation methods of space cooling load, where ΔQ_c (J) stands for space cooling load, Q_s (L/s) and Q_r (L/s) stand for the air flow rate of supply and return air, respectively, ρ_s (kg/m3) and ρ_r (kg/m3) stand for the air density of supply and return air, respectively, i_s (kJ/kg) and i_r (kJ/kg) stand for the enthalpy of supply and return air, respectively. With formula 3.47 to 3.51, the cooling load caused by heat gain through building envelope could be calculated.

$$\mathrm{i} = 1.01t + (2500 + 1.84t)d \tag{3.47}$$

$$d = 622 \cdot \frac{\varphi \cdot P_q}{B - \varphi \cdot P_q} \tag{3.48}$$

$$P_q = e^{-\frac{5800.2206}{273.15+t}+1.3914993-0.04860239(273.15+t)+0.41764768\times10^{-4}(273.15+t)^2-0.14452093\times10^{-7}(273.15+t)^3+6.5459673\ln(273.15+t)}$$

(3.49)

$$\rho = 0.003484\frac{B}{273.15+t} - 0.00134\frac{\varphi \cdot P_q}{273.15+t} \tag{3.50}$$

$$\Delta Q_c = Q_s \rho_s i_s - Q_r \rho_r i_r \tag{3.51}$$

The fan coil unit (FCU) inside the room has three different supply air flow rate grades. Before monitor period, the air flow rates of FCU are measured. The FCU air flow rate of each grade is considered to be stable. Table 3.1 presents the measured result of the FCU air flow rate. During monitoring period, the flow rate grade setting is recorded.

Table 3. 1 Air flow rate measurement for FCU

Flow rate grates	**High (L/s)**	**Medium (L/s)**	**Low (L/s)**
1st measurement	240	231	199
2nd measurement	236	236	199
3rd measurement	239	229	193
4th measurement	245	234	197

5th measurement	243	238	198
6th measurement	241	231	196
Average	240.7	233.2	197

Due to the limitation of space, only one office room is provided for monitoring. In order to eliminate the impact of weather, cooling load data under similar weather is selected for comparing in each group of comparison.

3.4.3 Error Analysis

According to error propagation formulas, the errors of indirect variables from formula 3.47 to 3.51 could be calculated as follows:

$$\frac{\delta_i}{i} = \sqrt{\left(\frac{\delta_t}{t}\right)^2 + \left(\frac{\delta_d}{d}\right)^2} \tag{3.52}$$

$$\frac{\delta_d}{d} = -\sqrt{\left(\frac{\delta_{P_q}}{P_q}\right)^2 + \left(\frac{\delta_\varphi}{\varphi}\right)^2} \tag{3.53}$$

$$\frac{\delta_{P_q}}{P_q}=\sqrt{\left(\frac{5800.2206t}{(273.15+t)^2}-0.04860239t+0.83529536\times10^{-4}\times(273.15+t)t-0.43356279\times10^{-7}(273.15+t)^2t+\frac{6.5459673t}{273.15+t}\right)^2}\frac{\delta_t}{t}$$

(3.54)

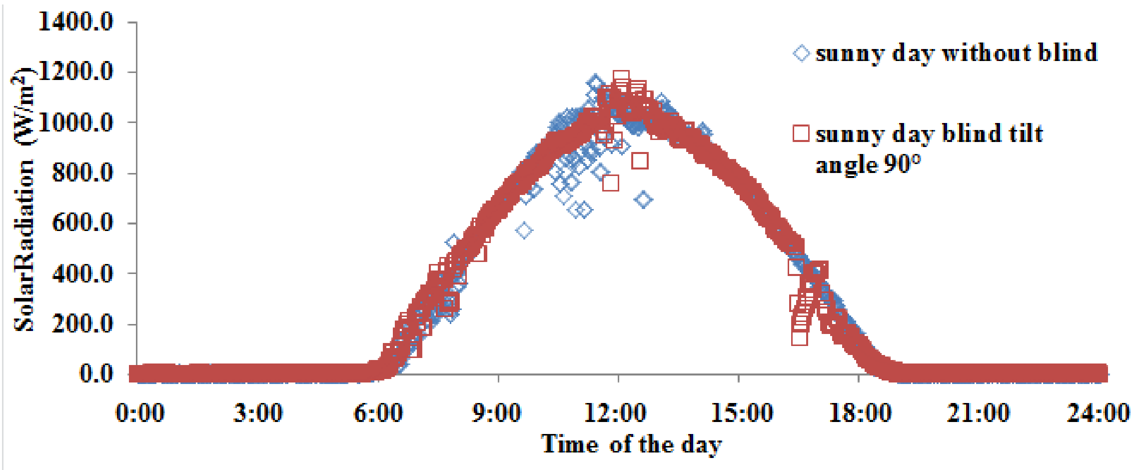
$$\frac{\delta_\rho}{\rho}=-\frac{\delta_t}{t}-\sqrt{\left(\frac{\delta_{P_q}}{P_q}\right)^2+\left(\frac{\delta_\varphi}{\varphi}\right)^2+\left(\frac{\delta_t}{t}\right)^2} \tag{3.55}$$

$$\frac{\delta_{Q_c}}{Q_c}=\sqrt{\left(\frac{\delta_i}{i}\right)^2+\left(\frac{\delta_\rho}{\rho}\right)^2+\left(\frac{\delta_Q}{Q}\right)^2} \tag{3.56}$$

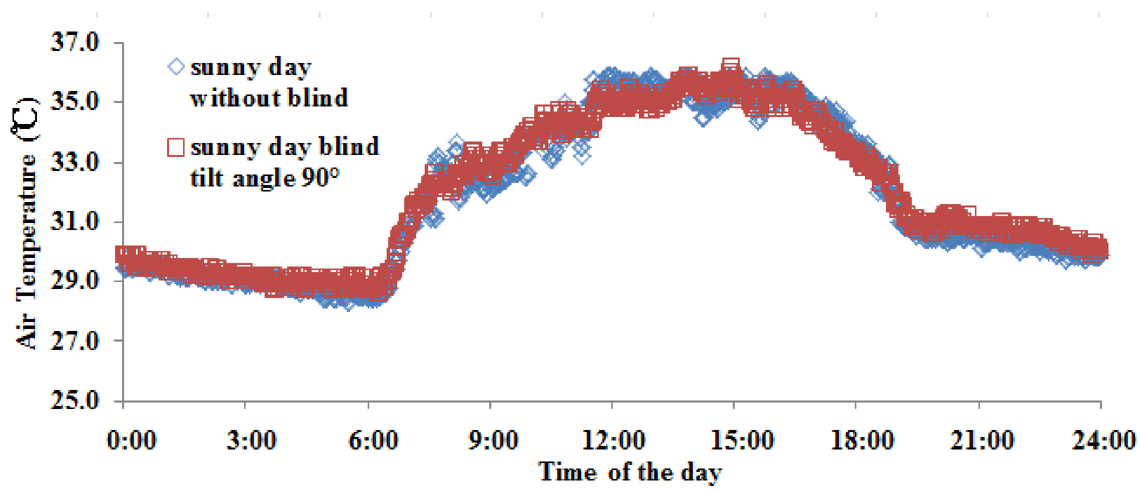
From formula 3.52 to 3.56, the relative error of cooling load measurement could be calculated as $\frac{\delta_{Q_c}}{Q_c}=6.2\%$.

3.4.4 Measurement Result and Discussion

Measurement data in two sunny days are selected to study the thermal performance of interior blind. One group of data is taken while there is no interior blind installed on window area (taken on June 1st). The other group of data is taken while window area is covered by interior blind and the tilt angle of blind louver is 90° (taken on June 2nd). Figure 3.4 gives the total solar radiation and outdoor air temperature during the two sunny days for reference.



A. Solar radiation



B. Air temperature

Figure 3. 4 Comparison of the weather data of the two sunny days

A dimensionless parameter Δ is defined to make a quantitative comparison of weather data between these two sunny days. The definition of Δ is presented in Formula 3.57 and 3.58.

$$\Delta_e = \left(\frac{\sum_n |e_{Ai} - e_{Bi}|}{n} \right) \Big/ \overline{e_A} \tag{3.57}$$

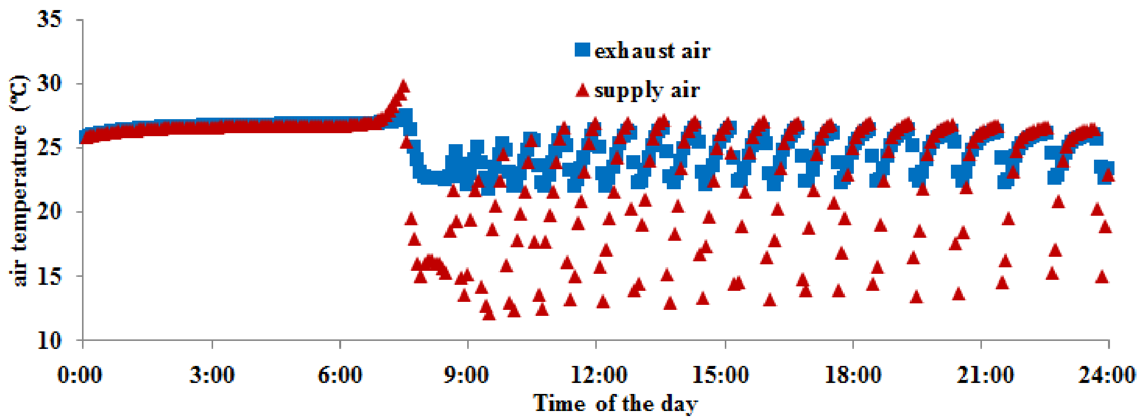
$$\Delta_t = \left(\frac{\sum_n |t_{Ai} - t_{Bi}|}{n} \right) \Big/ \overline{t_A} \tag{3.58}$$

Δ_e stands for the relative deviation of solar radiation between two days. e_{Ai} (W/m^2) and e_{Bi} (W/m^2) stand for solar radiation data obtained every minute during the two days. $\overline{e_A}$ (W/m^2) stands for the average solar radiation level of the first day. Δ_t stands for the relative deviation of outdoor air temperature between two days. t_{Ai} (℃) and t_{Bi} (℃) stand for outdoor air temperature data obtained every minute during the two days. $\overline{t_A}$ (℃) stands for the average outdoor air temperature of the first day.

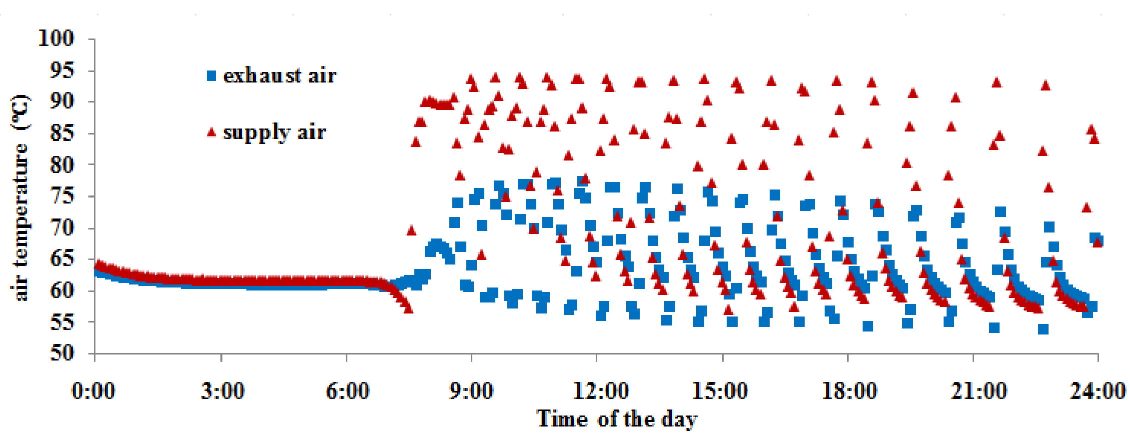
Based on formula 3.57 and 3.58, the relative deviations of solar radiation and outdoor air temperature between the above two sunny days can be calculated:

$$\Delta_e = 2.85\%, \ \Delta_t = 1.19\% \tag{3.59}$$

It is clear that the weather conditions are very similar in these two days. The difference between cooling loads of two days could be considered to be caused by the application of blind. Figure 3.5 presents the difference of air temperature and relative humidity between supply air and return air when no interior blind is installed on window area. Figure 3.6 presents the difference of air temperature and relative humidity between supply air and return air when interior blind is installed on window area with a tilt angle of 90 °. Figure 3.7 gives the calculation result of the instantaneous cooling load during the two sunny days.

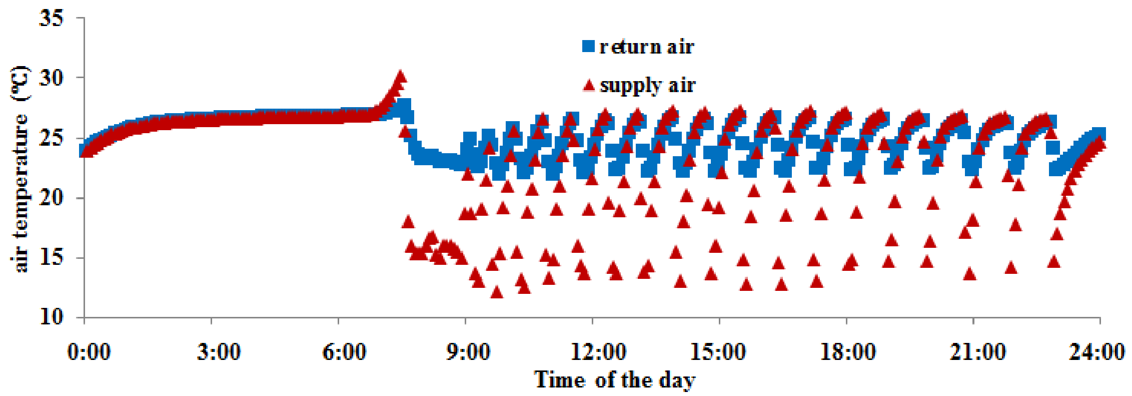


A. Air temperature

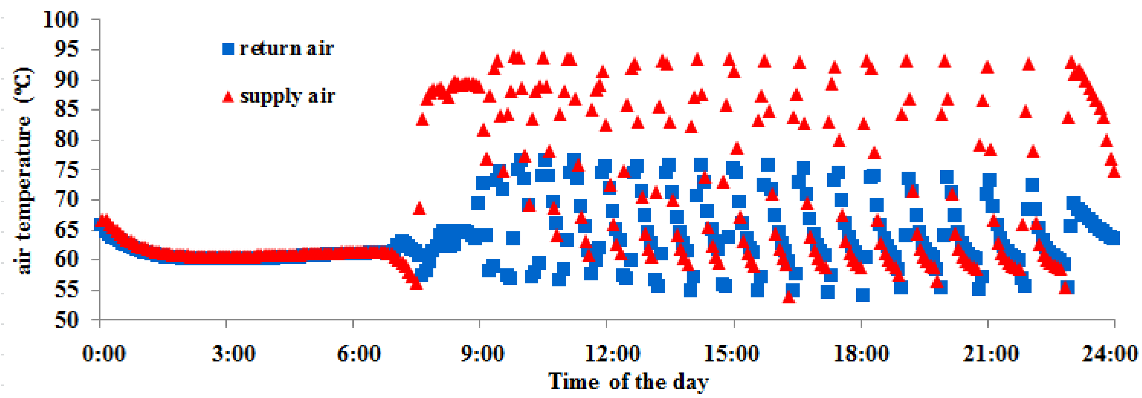


B. Air Relative Humidity

Figure 3. 5 Monitored supply and return air temperature and relative humidity without the blinds

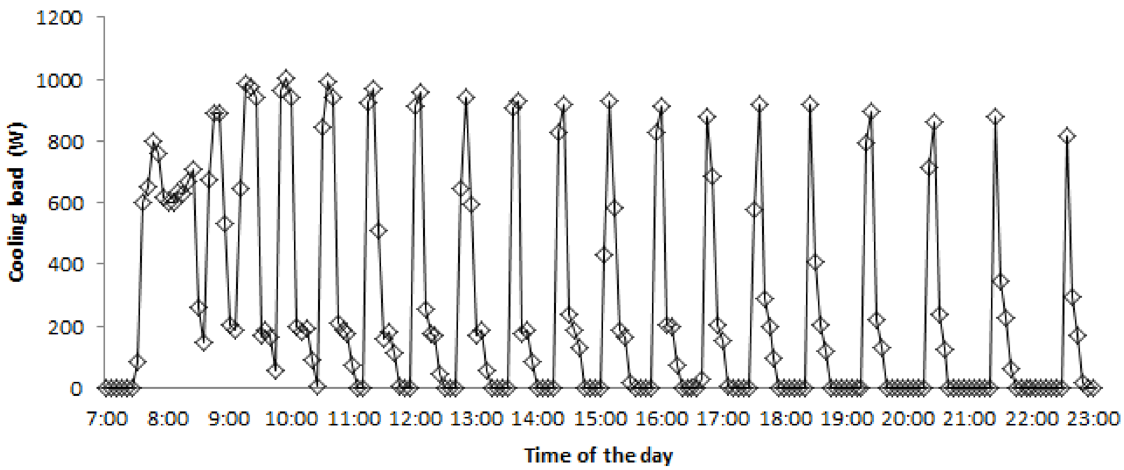


A. Air temperature

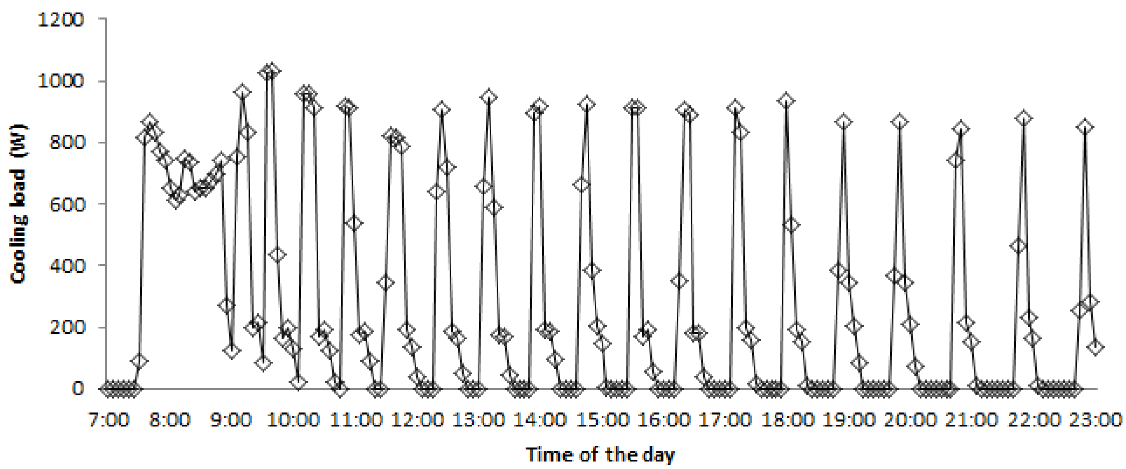


B. Air Relative Humidity

Figure 3. 6 Monitored supply and return air temperature and relative humidity with the blinds



A. Sunny day without blinds



B. Sunny day with blinds

Figure 3. 7 Calculation result of the instantaneous cooling load during two sunny days

During these two sunny days, the flow rate grade of FCU is set at "Low", the air flow rate into the room is 197 L/s. The air-conditioning system operates non-stop from 7:00 to 23:00. Calculating with Formula 3.47 to 3.51, the cooling load in the office room in sunny day without blind application is 5.07×10^{7} J. The cooling load in sunny day with blind tilt angle at 90 °is 4.63×10^{7} J.

With the application of interior blind in the east-facing office room, a cooling load reduction of around 8.7% could be expected on cooling load caused by heat gain through building envelope. Figure 3.8 gives the cooling load reduction during every hour from 7:00 to 23:00 after the application of interior blind. It is clear that the performance of interior blind is largely affected by the amount of solar direct radiation. Due to the office room's east orientation, the performance of blind in the morning is better than that in afternoon. It is also clear that the peak cooling load appears at around 8:00 or 9:00 in the morning, which is also the result of the east orientation.

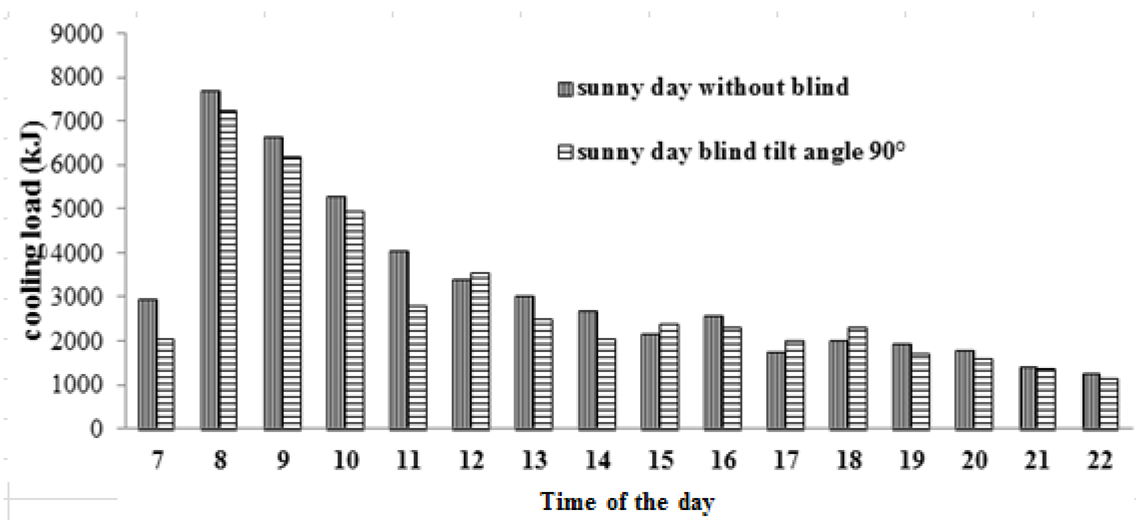
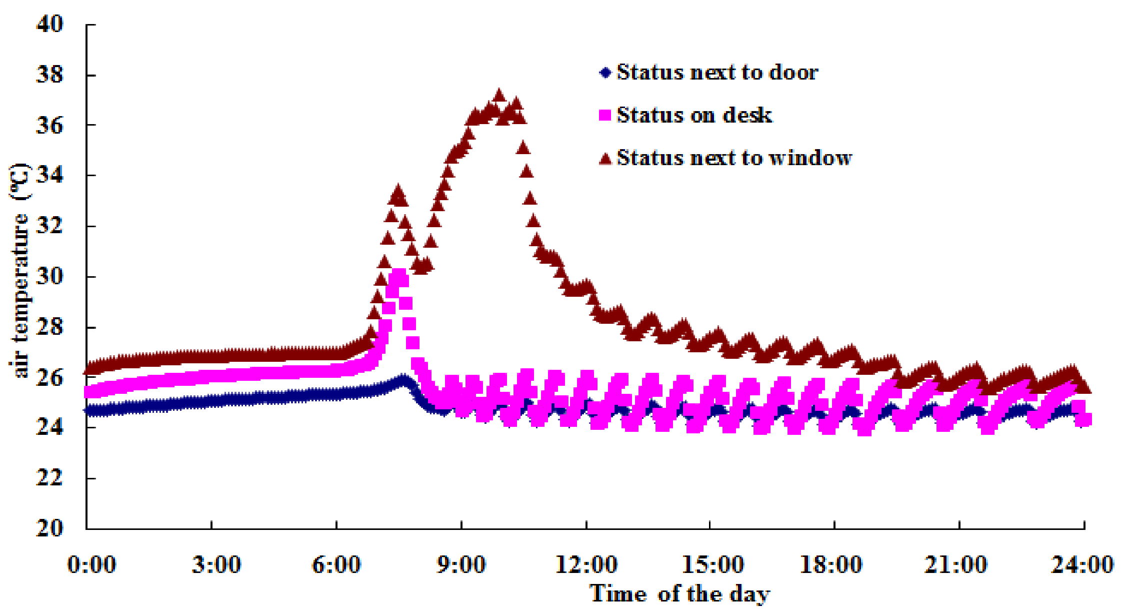
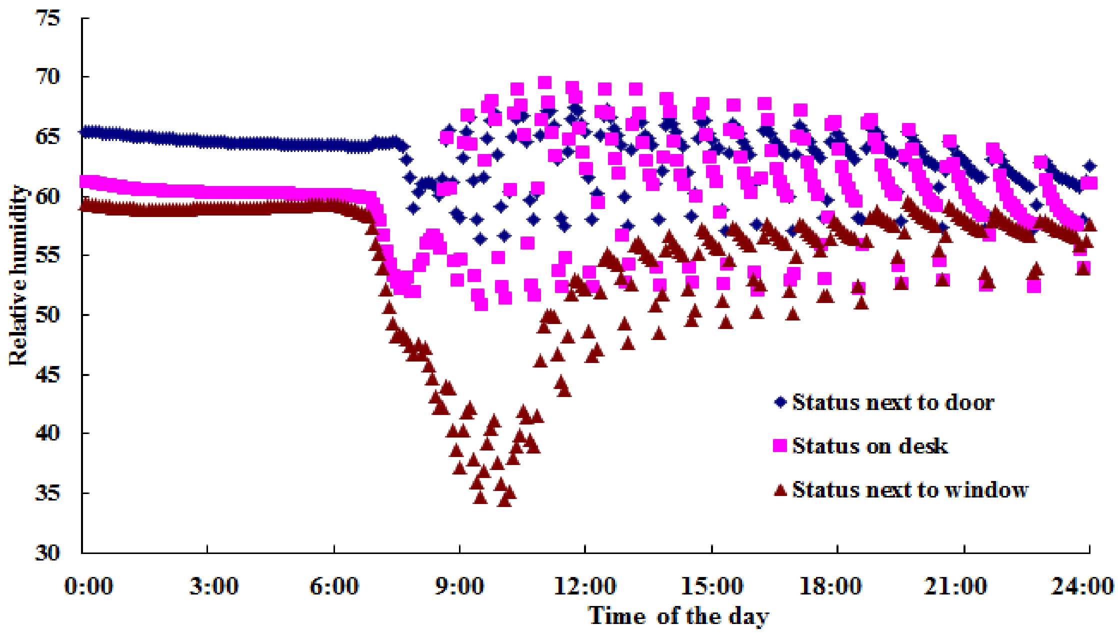


Figure 3. 8 Cooling load reduction with the application of interior blind in sunny day

Besides cooling load reduction, the application of the interior blinds can also help to maintain a more uniform thermal condition. As mentioned above, three measuring points are settled in the office room: one next to the window, one on the desk and one next to the door. Figure 3.9 and Figure 3.10 give the temperature and humidity distribution within the office room in sunny day with and without blind application. It is clear that with the application of the interior blind, the temperature and humidity differences among different zones within the office are smaller. The air status distribution within the room is an important index to assess the indoor thermal comfort environment.

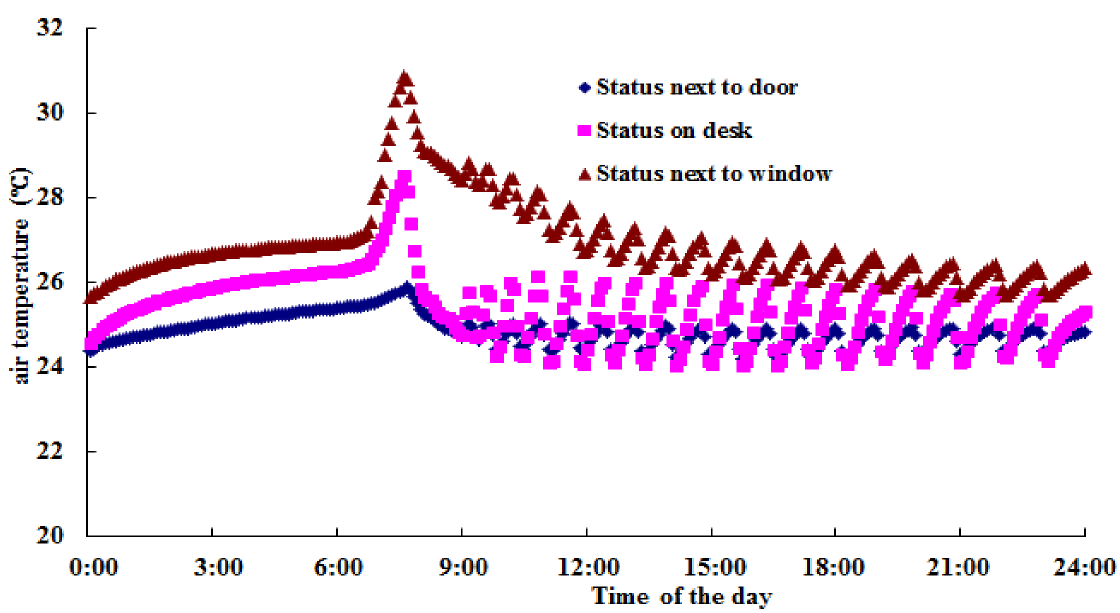


A. Air temperature

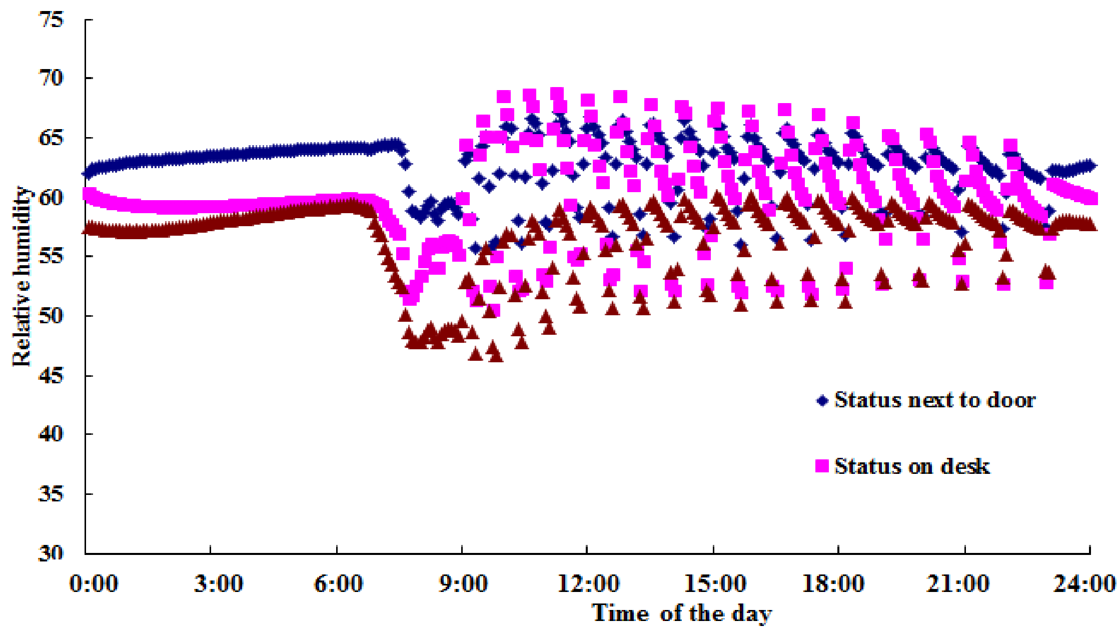


B. Air Relative Humidity

Figure 3. 9 Status difference among three measuring points in sunny day without blind application



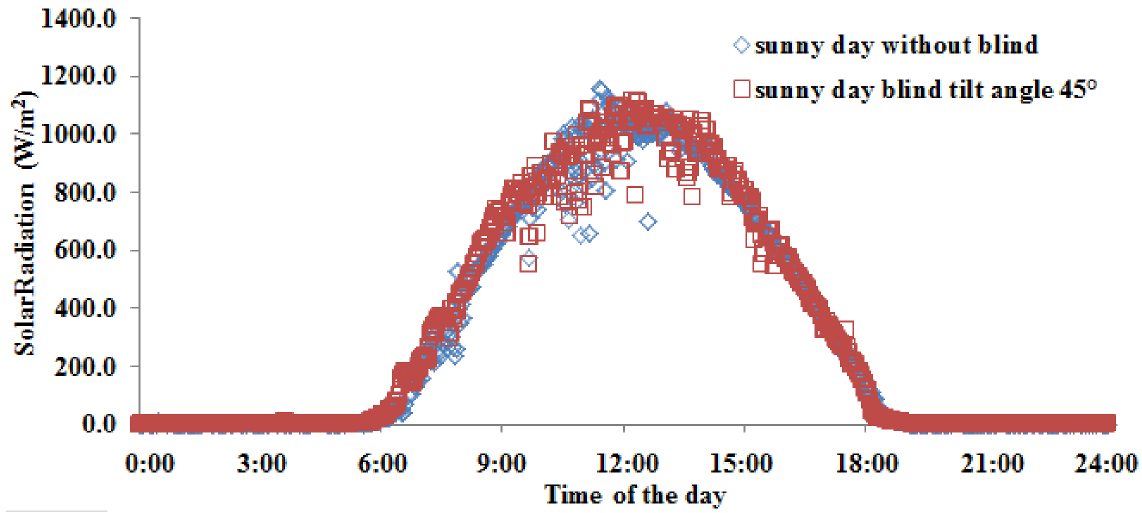
A. Air temperature



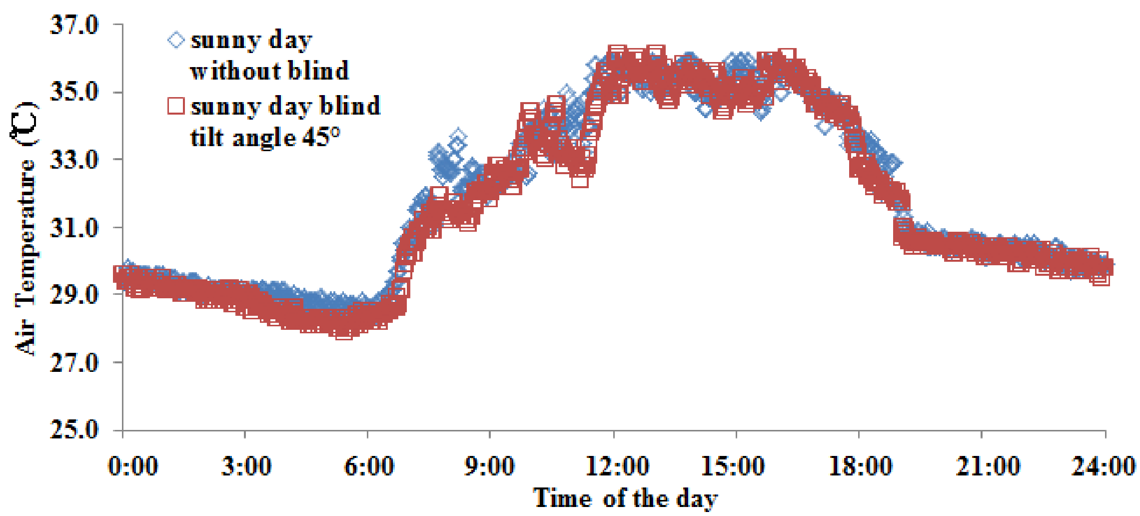
B. Air Relative Humidity

Figure 3. 10 Status difference among three measuring points in sunny day with blind application

In order to receive a full evaluation of interior blind performance, measurement in another sunny day is also conducted, during this sunny day (June 10th), the tilt angle of blind louver is fixed at 45 °. Figure 3.11 gives the comparison of weather data between the day without blind application and the day while the tilt angle of blind louver is 45 °.



A. Solar radiation



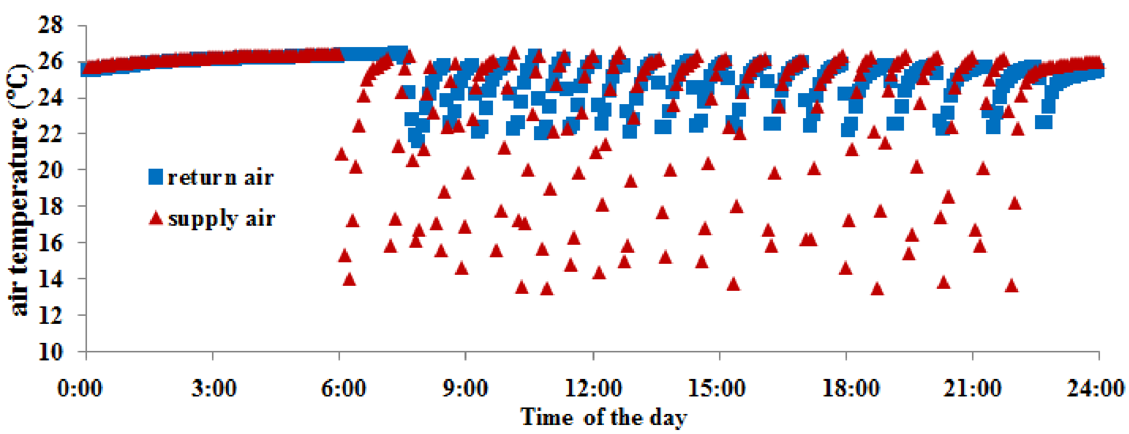
B. Air temperature

Figure 3. 11 Comparison of the weather data of the two sunny days

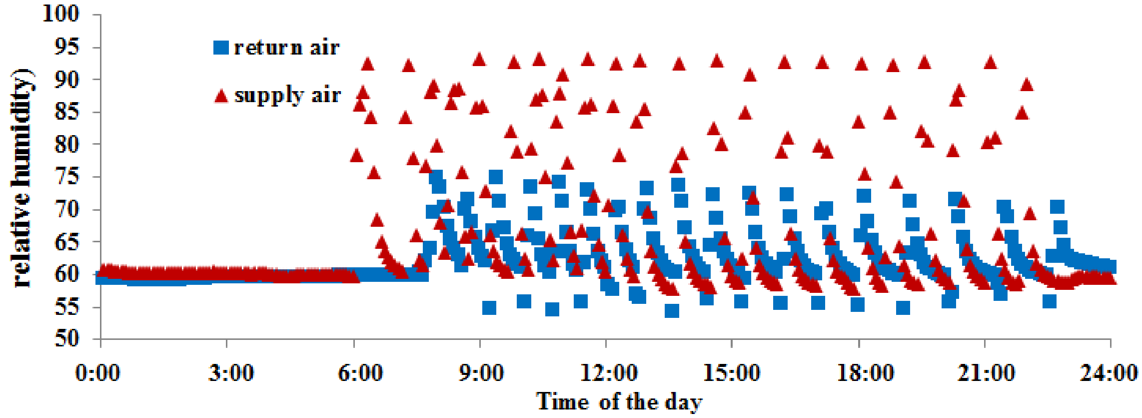
Based on Formula 3.57 and 3.58, the relative deviations of solar radiation and outdoor air temperature between the above two sunny days can be calculated:

$$\Delta_e = 3.77\%\,,\ \Delta_t = 1.25\% \tag{3.60}$$

The weather conditions of these two days are very similar. The difference of cooling load between these two days can be considered to be caused by the application of blind. Figure 3.12 presents the difference of air temperature and relative humidity between supply air and return air during the sunny day when interior blind is applied on window area with a tilt angle of 45 °. Figure 3.13 gives the calculation result of the instantaneous cooling load when blind louver tilt angle is 45 °. From Figure 3.13 it is clear that the cooling load in the morning is still larger than that in the afternoon. Calculating with Formula 3.46 to 3.51, the cooling load of the office room in sunny day with blind louver tilt angle at 45 ° is 4.11×10^7 J. a reduction of around 18.7% is achieved.



A. Air temperature



B. Air Relative Humidity

Figure 3. 12 Monitored supply and return air temperature and humidity with the blinds (louver tilt angle at 45 °)

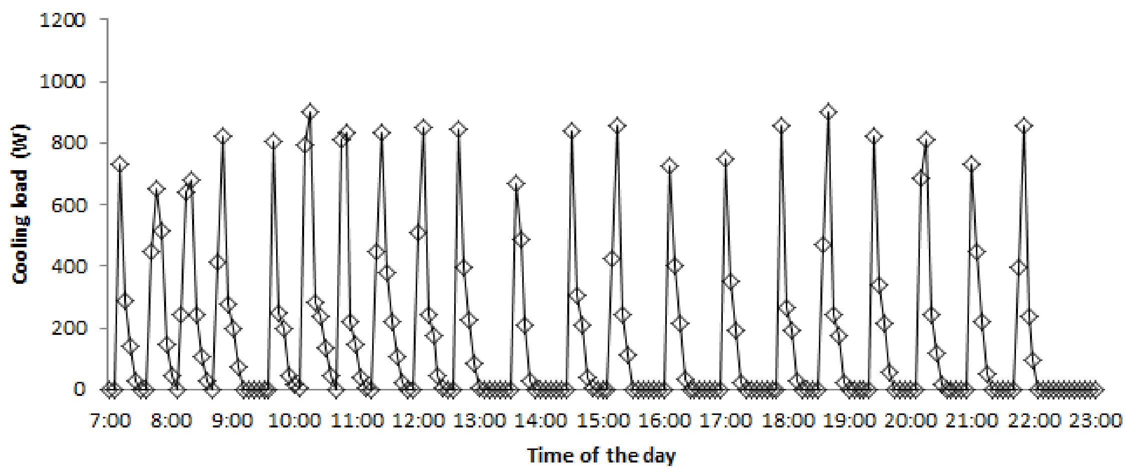


Figure 3. 13 Calculation result of the instantaneous cooling load with louver tilt angle at 45 °

In the following thermal property research, simulation based on EnergyPlus is the major research method. The reliability of the simulation result is a major concern. In order to enhance the reliability of the simulation result, a simulation based on the same office involved in the on-site measurement is completed. Actual measured weather data is used as input to simulate the envelope heat gain of the monitored office. The indoor air temperature set point is 25℃. The air-conditioning system operates non-stop from 7:00 to 23:00. The thermal property of external wall materials used in the simulation is listed in Table 3.2 below. The window glass material used in the simulation is normal 6mm thick single layer glass, with a solar transmittance of 0.71, and a conductivity of 1.046 W/mK.

Table 3. 2 Thermal property of external wall materials

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
White mosaic tile	0.005	1.5	2500	840
Cement render	0.01	0.72	1860	840
Concrete panel	0.1	2.16	2400	657
Gypsum plaster	0.01	0.51	1120	960

Figure 3.14 gives the comparison between simulation and on-site measurement result while blind tilt angle is set at 90°. Figure 3.15 gives the comparison between simulation and on-site measurement result while blind tilt angle is set at 45°. As shown in Figure 3.14 and 3.15, a generally good agreement is achieved between experiment and simulation results. Due to the room's east orientation, solar heat gain in the morning is higher than that in the afternoon. The peak cooling load occurs at 8:00. The blind also performs better in the morning. In the afternoon while no direct radiation is projected on the window surface, the effect of blind becomes less obvious. When blind tilt angle is set

at 90 °, the simulated cooling load of the office room with and without the blinds are 5.38×10^7 J and 6.10×10^7 J, respectively. A difference of 11.8% is found, whereas in the measurement the difference is 8.7%. When blind tilt angle is set at 45 °, the simulated cooling load of the office room with blinds is 4.65×10^7 J. A reduction of 23.9% is calculated, whereas in the measurement the reduction is 18.9%. One reason that may causes the deviation between simulation and measurement result may be the divergence of material thermal properties between simulation and actual situation. Since the office building has been in function for quite a long time, the properties of surface material and the reflectivity of interior blind may have changed. Besides, there exist many other buildings surrounding. These surrounding buildings can block part of radiation that should have been projected on the wall surface. With the decreasing of radiation projection, the performance of interior blind also decreases. Another reason may lies in the uneven distribution of indoor temperature. As shown in Figure 3.9 and 3.10, there exist differences among air temperature of different zones. While in simulation, the air temperature within the office room is considered to be uniform.

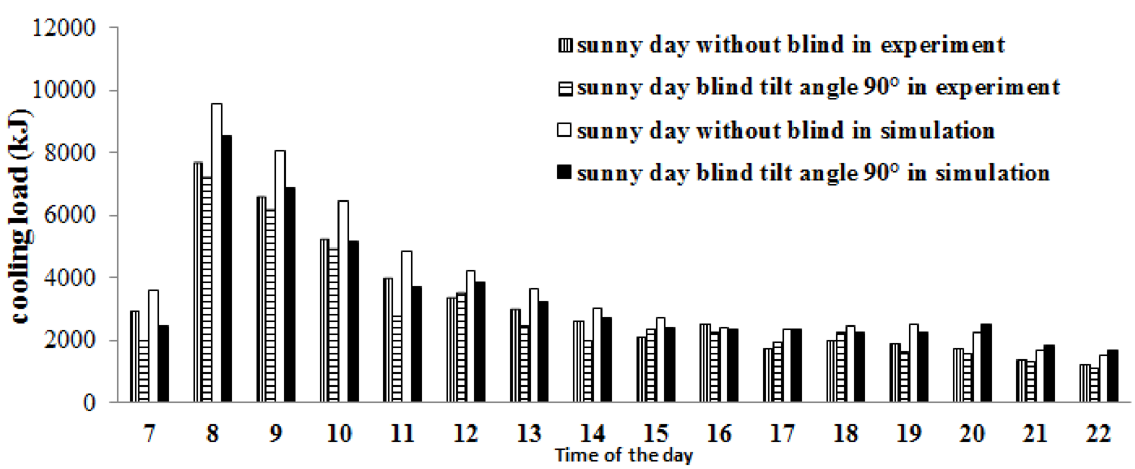


Figure 3. 14 Comparison between results from the simulation and the on-site measurement with and without the blinds

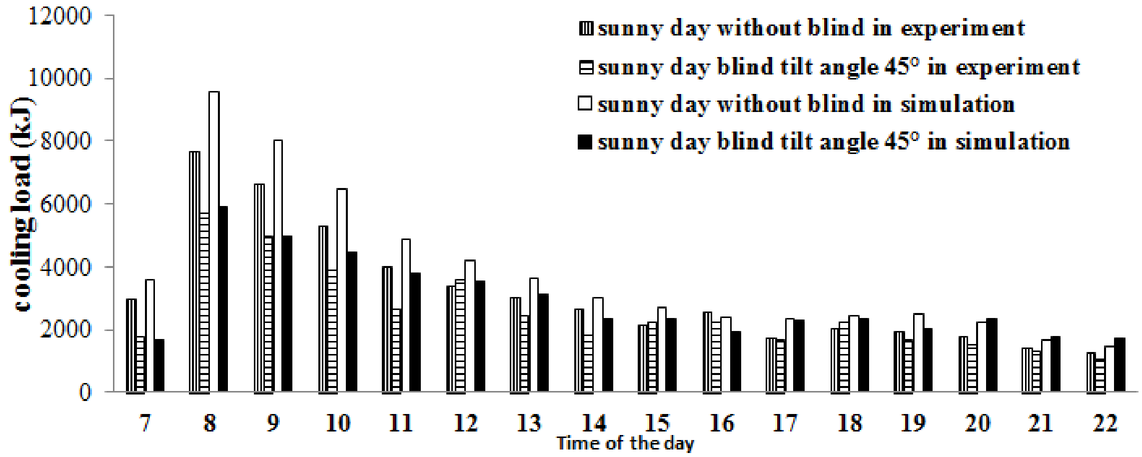


Figure 3. 15 Comparison between results from simulation and on-site measurement with and without the blinds (louver tilt angle at 45 °)

3.5 Summary

In this chapter, the research methods applied in this study are presented. The basic principle of these methods has been introduced. The equipment utilized in these methods has been listed and introduced.

The main research method selected for this research is building energy simulation with the application of two popular building energy simulation programs. The model building is presented in detail. An on-site measurement is also arranged for direct perception of the energy-efficient building envelope designs. The setup of reference points is described. The measurement method is also described.

Chapter 4

Thermal Performance of Energy-Efficient Window Designs

4.1 Introduction

Window glazing area is an important and indispensable component in almost all kinds of buildings. Window could let in necessary daylight to make the visual environment comfortable and meanwhile provide the occupants with a pleasure view of outside world, both of which are quite necessary and effective for a high working efficiency and pleasant life.

Glazing is transparent material with high thermal conductivity. Heat gain through window area takes the majority in building envelope heat gain. Generally speaking, there are two common ways to improve the thermal performance of window. First, energy-efficient window glazing materials can be applied to replace conventional single-layer glass. It is known that infrared radiation contains the majority of solar energy. Introduction of glazing materials that could let in visible light and block out infrared radiation can significantly reduce radiation heat gain. Second, the application of shading device is also an effective way of reducing solar heat gain. In this chapter, popular energy-efficient designs on window area are simulated and discussed. The impacts of variable factors are investigated.

4.2 Simulation Model Construction

4.2.1 Brief Information of the Building Model

The simulation research is based on a high-rise building. The structure of the building remains the same in all simulation cases. The overall appearance of the building is shown in Figure 4.1. The building is a square building with north-south orientation, with an floor area of 100m ×100m. The building has 20 floors. The height of each floor is 3.2m. The window-wall ratio of each vertical façade remains the same at 0.375. Necessary partitions are also added inside the building. The layout of a typical floor is shown in Figure 4.2. It should be noticed that there exists an inside zone containing devices and elevators, which is not air-conditioned.

Four cities with different climates are selected. The four cities from south to north are Singapore, Hong Kong, Miami and Houston. All the four cities are located in Northern Hemisphere. Their latitudes are 1°18´, 22°15´, 25°47´ and 29°45´. Since over 75% of the world populations live within 20°~60° north latitude, the selection of these four cities is representative and practical. Within these four cities, solar elevation angle at the same time decrease from south to north. All the four cities are located within cooling-dominant climate zones.

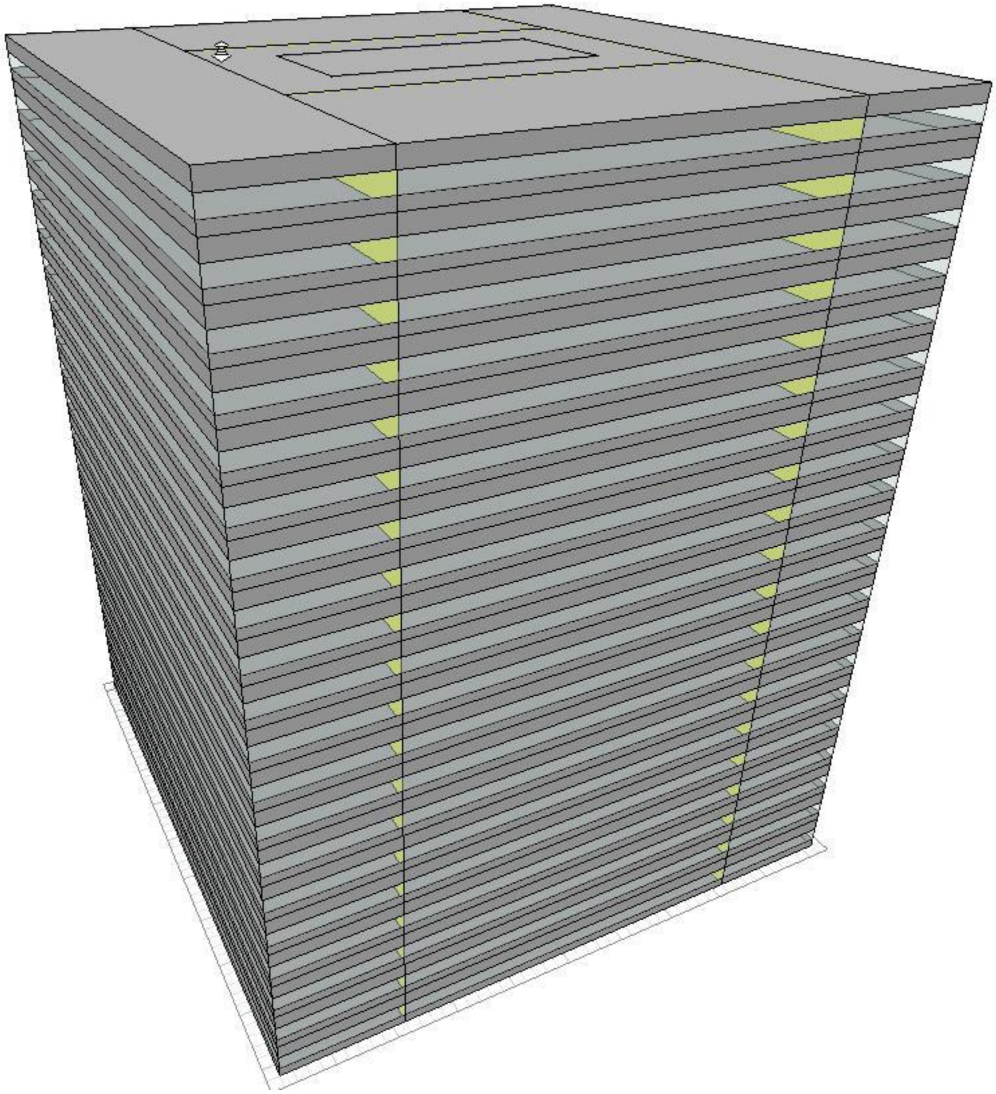


Figure 4. 1Exterior appearance of the building

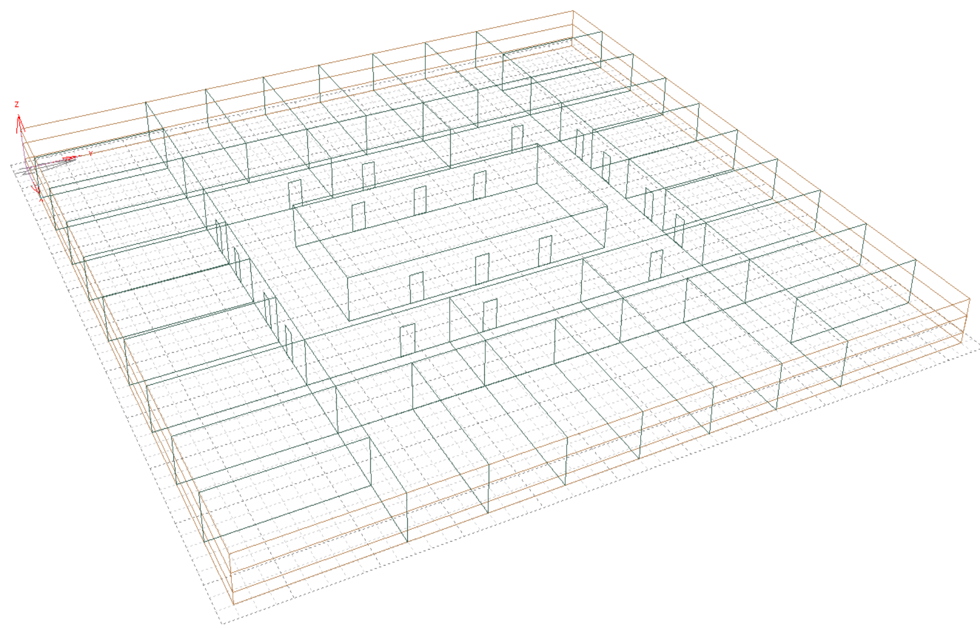


Figure 4. 2 Partition of each floor within the building

4.2.2 Important Material Settings of the Building Model

The details of building construction, including structure and materials of wall, roof, ceiling, floor and window are defined strictly according to local standards of building design (Hong Kong Government, 1995; Singapore Government, 2008; The U. S. Department of Energy, 2008). The detailed structure and parameters of wall and roof are shown in Table 4.1. The window glass material applied in all 4 cities is the normal 6mm thick single layer glass, with a solar transmittance of 0.71, and conductivity of 1.046 W/mK.

Table 4. 1 Detailed data of building materials

A. Wall in Hong Kong and Singapore

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
White mosaic tile	0.005	1.5	2500	840
Cement render	0.01	0.72	1860	840
Concrete panel	0.1	2.16	2400	657
Gypsum plaster	0.01	0.51	1120	960

B. Roof in Hong Kong and Singapore

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
Concrete tiles	0.025	1.1	2100	657
Asphalt	0.02	1.2	2300	1700
Cement screed	0.05	0.72	1860	840
Expanded polystyrene	0.05	0.035	23	1470
Concrete	0.15	2.16	2400	657
Gypsum plaster	0.01	0.51	1120	960

C. Wall in Houston and Miami

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
1IN stucco	0.0253	0.6918	1856	837
8IN concrete HW	0.2032	1.311	2240	837
½ IN gypsum	0.0127	0.16	785	830

D. Roof in Houston and Miami

material	Thickness(m)	Conductivity(W/mK)	Density(kg/m^3)	Specific heat(J/kgK)
Roof membrane	0.0095	0.16	1121	1460
IEAD NonRes roof	0.0125	0.049	265	837
Metal decking	0.0015	45	7680	418

For external window area transparent insulation, several glazing materials are selected. Besides conventional single-layer and multi-layer glazing, four different kinds of low-e glazing are also chosen for simulation research. The thermal and optical parameters of the four kinds of selected low-e glass are listed in Table 4.2. T_{sol} stands for solar radiation transmittance. R_{sol1} stands for front side solar radiation reflectivity. R_{sol2} stands for back side solar radiation reflectivity. T_{vis} stands for visible light transmittance. R_{vis1} stands for front side visible light reflectivity. R_{vis2} stands for back side visible light reflectivity. T_{ir} stands for infrared transmittance. E_1 stands for front side infrared emissivity. E_2 stands for back side infrared emissivity. The thickness of all the low-e glass is 6mm. Two most commonly applied shading designs are simulated in the study. For interior blind application, the material of the blind louvers is aluminum. For overhang application, the material of the overhang is the same as the building envelope surface.

Table 4. 2 Thermal and optical parameters of selected low-e glass

	Case A	Case B	Case C	Case D
T_{sol}	0.598	0.591	0.555	0.4
R_{sol1}	0.074	0.144	0.280	0.281
R_{sol2}	0.109	0.199	0.180	0.403

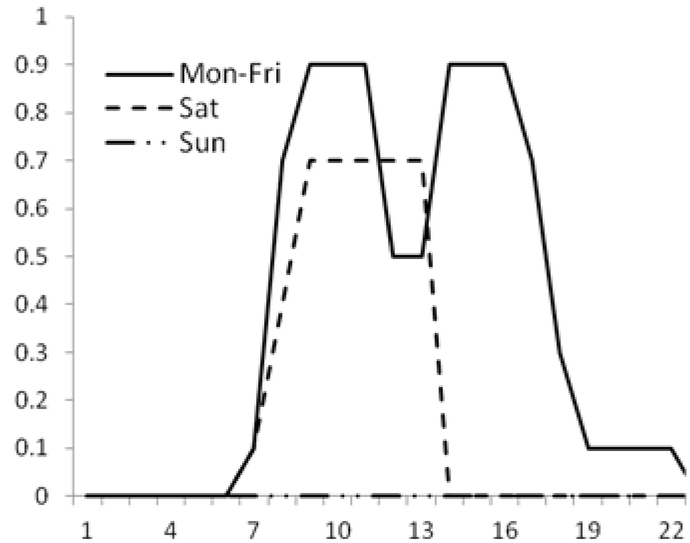
T_{vis}	0.805	0.803	0.853	0.742
R_{vis1}	0.087	0.068	0.059	0.064
R_{vis2}	0.096	0.062	0.079	0.052
T_{ir}	0	0	0	0
E_1	0.84	0.84	0.84	0.84
E_2	0.204	0.12	0.05	0.05

4.2.3 Important Operation Data Setting during Simulation

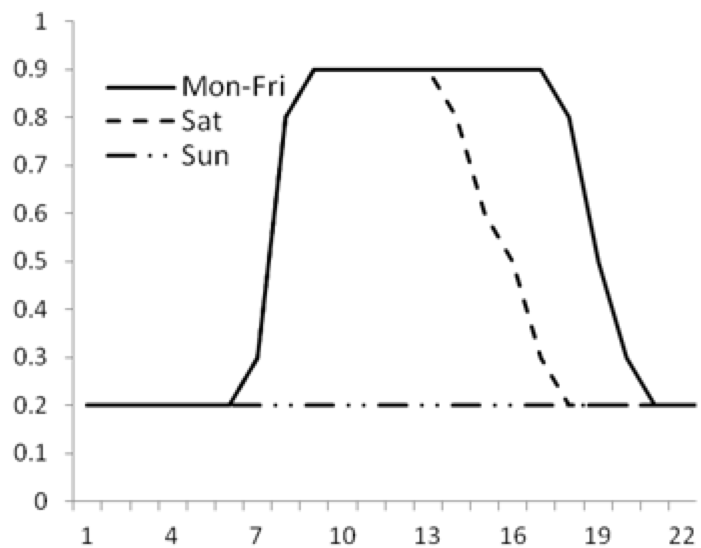
Three types of typical commercial buildings are simulated in this investigation, namely office, hotel and shopping mall, the settings for occupant density, lighting power density, equipment density and the minimum fresh air supply are presented in Table 4.3. The operation schedules of occupant, lighting and equipment are presented in Figure 4.3. It should be noted that in air-conditioning schedule, "1" on y-axis stands for "ON" status for air-conditioning system while "0" stands for "OFF" status. It should also be noticed that during the simulation of office and hotel buildings in Houston and Miami, the lighting power density is set at 10.76 W/m^2 (The U. S. Department of Energy, 2008).

Table 4. 3 Basic setting for occupant, lighting, equipment and fresh air supply

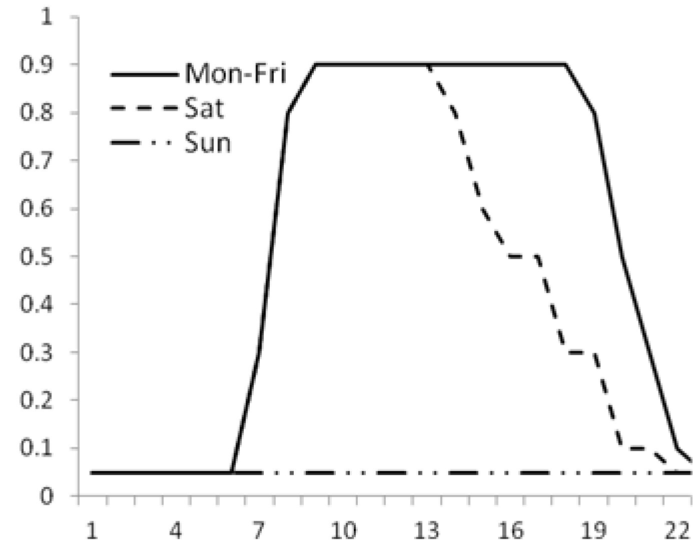
Types of building	Occupant density (m^2/person)	Minimum fresh air supply (L/s/person)	Lighting (W/m^2)	Electrical equipment (W/m^2)
Office building	13	8	15	10
Shopping mall	10	10	23	10
Hotel	25	30L/s per room	17	900W per room



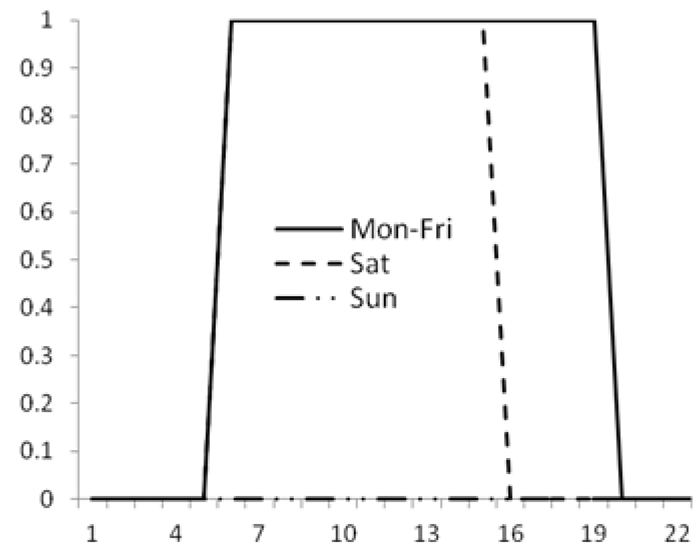
A1. Occupant



A2. Equipment

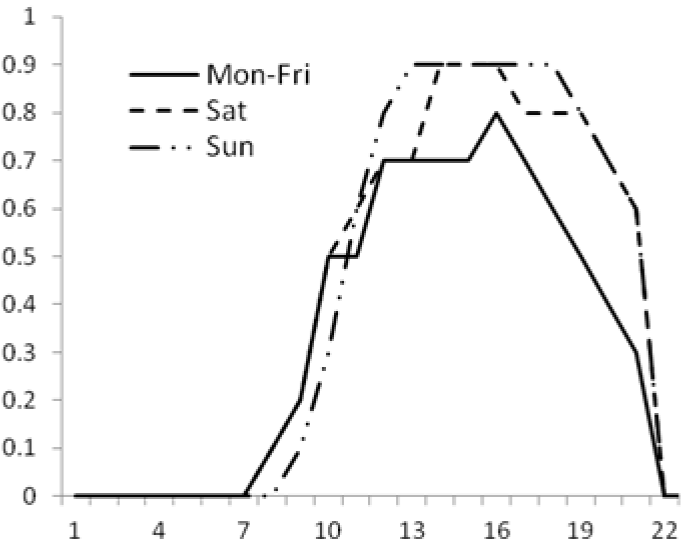


A3. Lighting

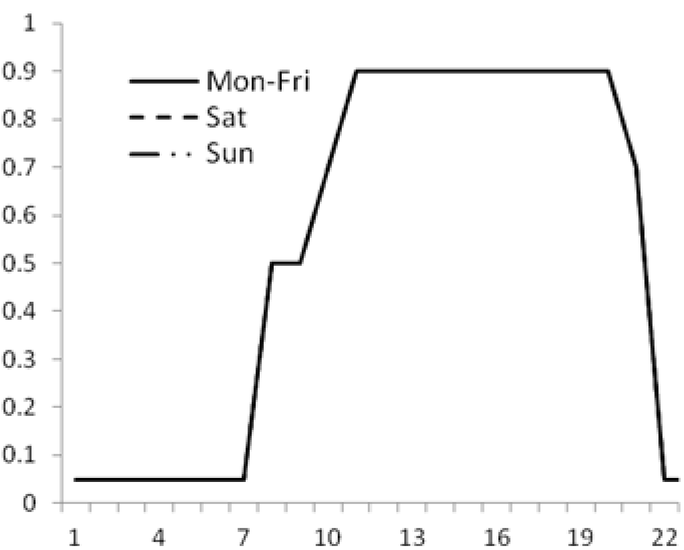


A4. Air-conditioning

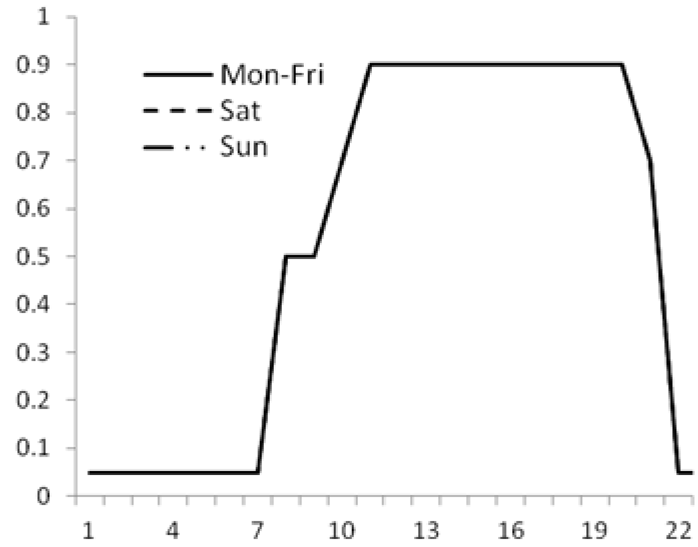
A. Office Schedule



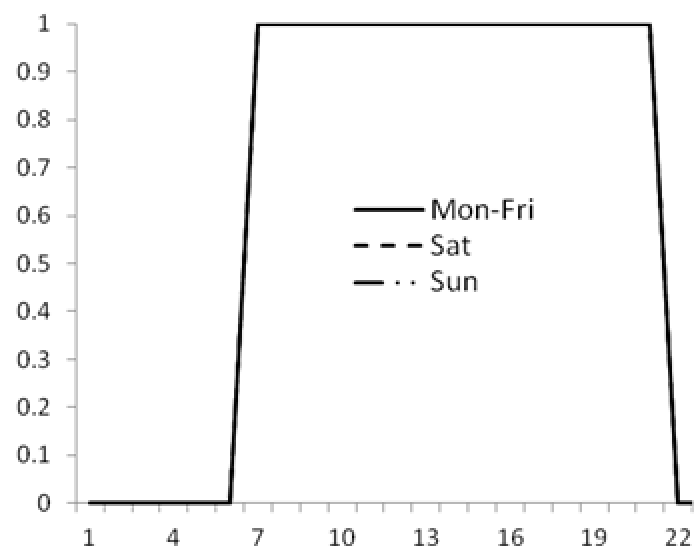
B1. Occupant



B2. Equipment

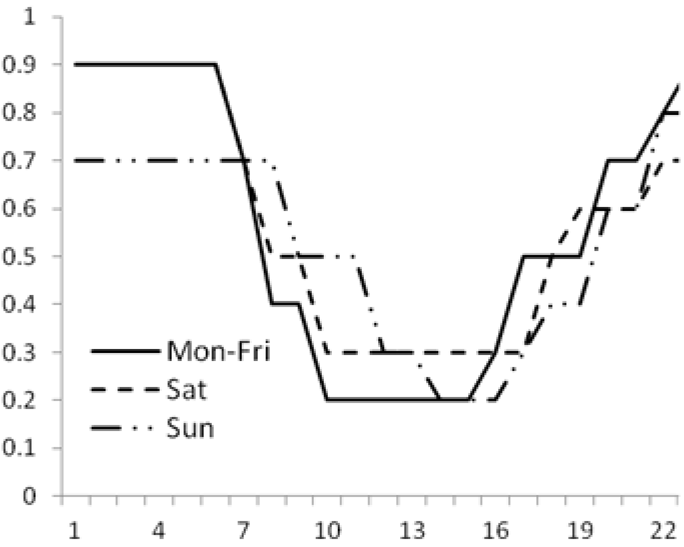


B3. Lighting

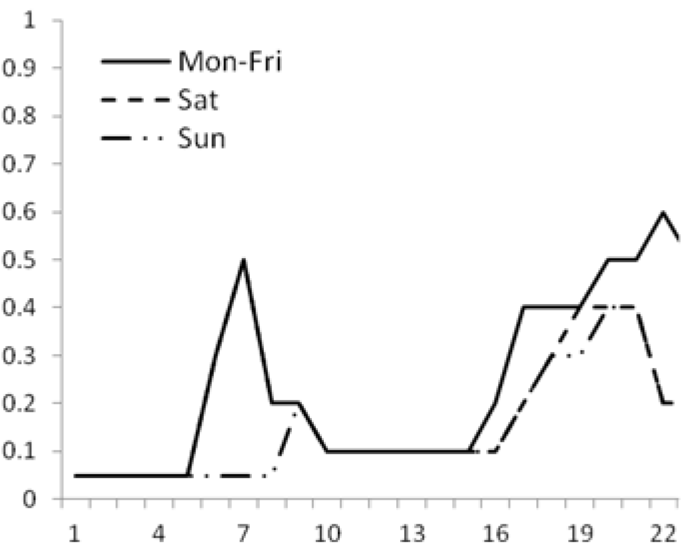


B4. Air-conditioning

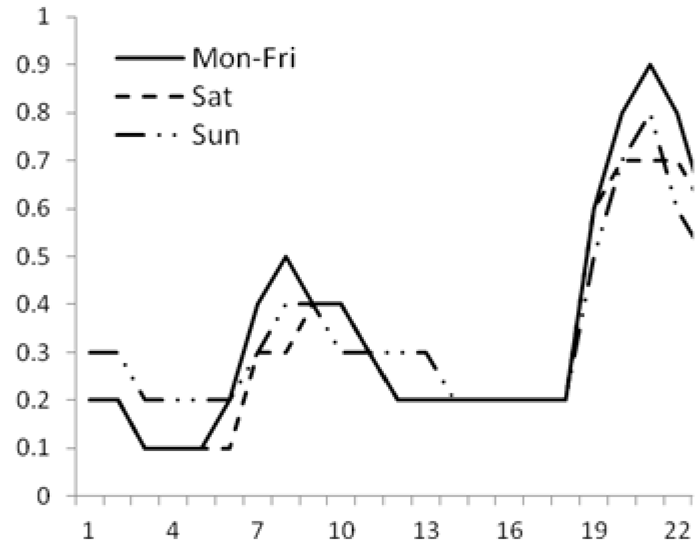
B. Shopping Mall Schedule



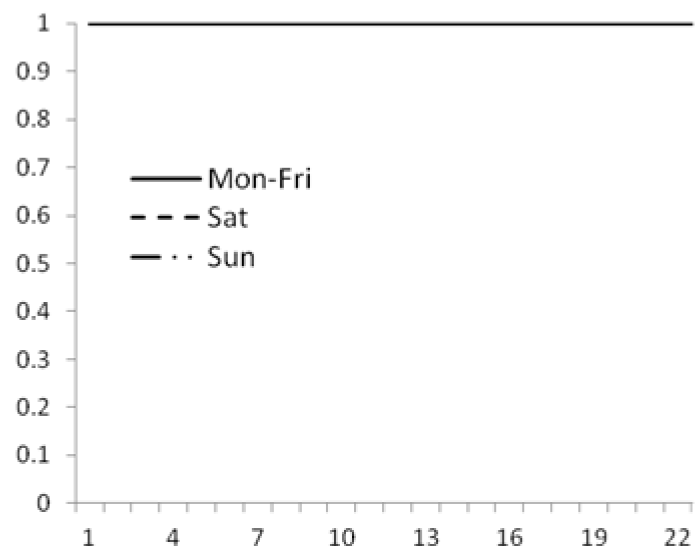
C1. Occupant



C2. Equipment



C3. Lighting



C4. Air-conditioning

C. Hotel Schedule

Figure 4. 3 Schedule setting for occupant, lighting, equipment and fresh air supply

Four cities with different climates are selected, Indoor thermostat could affect the heat transfer and cooling load largely, thus a temperature set point is very important for the simulation work. The guidance from local governments was referenced during the simulation. In the U.S., the Department of Energy suggested that during building energy simulation, indoor air temperature should be 24℃ (The U. S. Department of Energy, 2008). In Hong Kong, EMSD suggested the indoor air temperature to be 25±1℃ (Hong Kong Government, 2007). In Singapore, the government suggested that the indoor air temperature to be 24~26℃ (Singapore Government, 2009). In practical building energy investigation, the local guideline should be followed so that a practical result could be achieved. In this research, the thermal performance of different building envelope designs is the major concern. If indoor air temperature set points are different among cases the comparison is not quite strict. In order to make the discussion more strict and accurate, a consistent temperature set point of 25℃ is selected for all four cities. The simulation time step was 10 minutes, the simulation period was 1 year and the simulation results are reported on hourly basis.

An IdealLoadsAirSystem model is applied in the simulation research. This is a model offered by EnergyPlus Software which is specially designed for load calculation and evaluation. The model provides an ideal system to control the air temperature that meets all the load requirements. The model could keep zone air temperature at the set point according to pre-programmed HVAC operation schedule, so that heat gain within the air-conditioned zone during the operation period can be considered as the HVAC system load. It should be noted that any reheating and the associated overcooling that would be required in a realistic system are not calculated in such an ideal system model.

The cooling load caused by infiltration plays an important part in the building cooling load. In the simulation study, a consistent 1m^3/m^2h air infiltration is applied, so that the simulation result could be as realistic as possible (The U. S. Department of Energy, 2008).

4.3 Effects of Glazing Properties

4.3.1 Impact of Glazing Thickness of Single-Layer Glass

In the simulation base case, window glazing material is single-layer glass with a thickness of 6mm. The heat conductivity of glazing is highly affected by glass thickness. Table 4.4 presents heat gain changes under different glass thicknesses in all 4 cities.

Table 4. 4 Impact of glazing thickness on annual window heat gain

A1. Hotel in Singapore (kWh/m^2)

	south	east	north	west
origin	479.50	597.45	480.63	585.77
8mm	479.62	597.58	480.75	585.91
10mm	479.73	597.71	480.88	586.05
12mm	479.85	597.83	481.00	586.18

B1. Hotel in Hong Kong (kWh/m^2)

	south	east	north	west
origin	239.69	275.64	180.20	314.06
8mm	239.74	275.68	180.24	314.10
10mm	239.78	275.72	180.28	314.13
12mm	239.82	275.77	180.32	314.17

A2. Mall in Singapore (kWh/m^2)

	south	east	north	west
origin	480.25	599.39	481.34	586.27
8mm	480.43	599.59	481.52	586.47
10mm	480.61	599.78	481.71	586.67
12mm	480.79	599.97	481.89	586.86

B2. Mall in Hong Kong (kWh/m^2)

	south	east	north	west
origin	252.21	283.95	184.98	323.69
8mm	252.30	284.03	185.05	323.76
10mm	252.38	284.11	185.12	323.84
12mm	252.46	284.19	185.19	323.91

A3. Office in Singapore (kWh/m^2)

	south	east	north	west
origin	389.45	497.39	391.10	460.05
8mm	389.61	497.57	391.26	460.23
10mm	389.76	497.73	391.42	460.39
12mm	389.91	497.90	391.58	460.56

B3. Office in Hong Kong (kWh/m^2)

	south	east	north	west
origin	202.60	234.20	149.67	252.31
8mm	202.67	234.27	149.74	252.37
10mm	202.73	234.33	149.80	252.43
12mm	202.81	234.41	149.86	252.50

C1. Hotel in Miami (kWh/m^2)

	south	east	north	west
origin	404.69	423.31	231.43	490.38
8mm	404.81	423.43	231.52	490.50
10mm	404.93	423.55	231.61	490.62
12mm	405.04	423.67	231.69	490.74

D1. Hotel in Houston (kWh/m^2)

	south	east	north	west
origin	336.01	343.09	193.43	415.76
8mm	336.05	343.12	193.45	415.80
10mm	336.08	343.15	193.47	415.83
12mm	336.20	343.27	193.59	415.96

C2. Mall in Miami (kWh/m^2)

	south	east	north	west
origin	442.66	443.71	242.08	514.99
8mm	442.84	443.89	242.21	515.16
10mm	443.00	444.04	242.34	515.32
12mm	443.16	444.20	242.46	515.48

D2. Mall in Houston (kWh/m^2)

	south	east	north	west
origin	350.19	346.98	198.47	430.05
8mm	350.26	347.08	198.53	430.13
10mm	350.32	347.13	198.58	430.19
12mm	350.46	347.18	198.62	430.61

C3. Office in Miami (kWh/m^2)

	south	east	north	west
origin	349.83	366.38	195.33	395.18
8mm	349.71	366.37	195.30	395.16
10mm	349.83	366.50	195.39	395.28
12mm	349.95	366.62	195.48	395.40

D3. Office in Houston (kWh/m^2)

	south	east	north	west
origin	290.98	293.29	163.50	339.14
8mm	291.02	293.33	163.54	339.18
10mm	291.06	293.37	163.57	339.22
12mm	291.11	293.41	163.60	339.27

From Table 4.4 it is clear that in all cases, increasing thickness of single-layer glass cannot affect the thermal performance of window glazing. The reason is almost all the heat gain through window area is radiation heat gain that travels directly through transparent glass area, while conductive heat gain takes only a very little part. While selecting glazing material, thickness can be taken out from consideration. Similar conclusion could also be achieved from the simulation of double-layer glazing. Table 4.5 presents the thermal performance of double-layer glazing with different air layer thicknesses.

Table 4. 5 Impact of air layer thickness on annual window heat gain

A1. Hotel in Singapore (kWh/m^2) | **B1. Hotel in Hong Kong (kWh/m^2)**

	south	east	north	west		south	east	north	west
6mm	388.41	485.42	388.52	476.57	**6mm**	193.39	224.56	148.03	255.32
9mm	387.75	484.64	387.88	475.84	**9mm**	192.97	224.10	147.74	254.75
12mm	387.35	484.17	387.49	475.40	**12mm**	192.76	223.88	147.61	254.44

A2. Mall in Singapore (kWh/m^2) | **B2. Mall in Hong Kong (kWh/m^2)**

	south	east	north	west		south	east	north	west
6mm	390.83	488.94	390.84	478.70	**6mm**	203.74	231.86	152.54	263.68
9mm	390.48	488.50	390.51	478.29	**9mm**	203.50	231.58	152.44	263.28
12mm	390.27	488.22	390.30	478.02	**12mm**	203.47	231.59	152.42	263.10

A3. Office in Singapore (kWh/m^2) | **B3. Office in Hong Kong (kWh/m^2)**

	south	east	north	west		south	east	north	west
6mm	316.97	405.66	317.53	375.67	**6mm**	164.38	191.63	123.73	206.17
9mm	316.73	405.32	317.31	375.40	**9mm**	164.19	191.40	123.64	205.87
12mm	316.58	405.11	317.18	375.23	**12mm**	164.08	191.26	123.60	205.69

C1. Hotel in Miami (kWh/m^2) | **D1. Hotel in Houston (kWh/m^2)**

	south	east	north	west		south	east	north	west
6mm	323.05	343.18	190.74	397.10	**6mm**	267.25	278.13	158.92	337.50
9mm	322.55	342.76	190.54	396.51	**9mm**	266.50	277.66	158.50	336.70
12mm	322.24	342.51	190.42	396.15	**12mm**	266.06	277.25	158.23	336.21

C2. Mall in Miami (kWh/m^2) **D2. Mall in Houston (kWh/m^2)**

	south	east	north	west		south	east	north	west
6mm	354.47	360.52	200.49	419.19	**6mm**	279.70	281.75	163.70	349.94
9mm	354.08	360.24	200.44	418.74	**9mm**	279.03	281.15	163.35	349.21
12mm	353.89	360.12	200.45	418.50	**12mm**	278.80	281.13	163.22	348.85

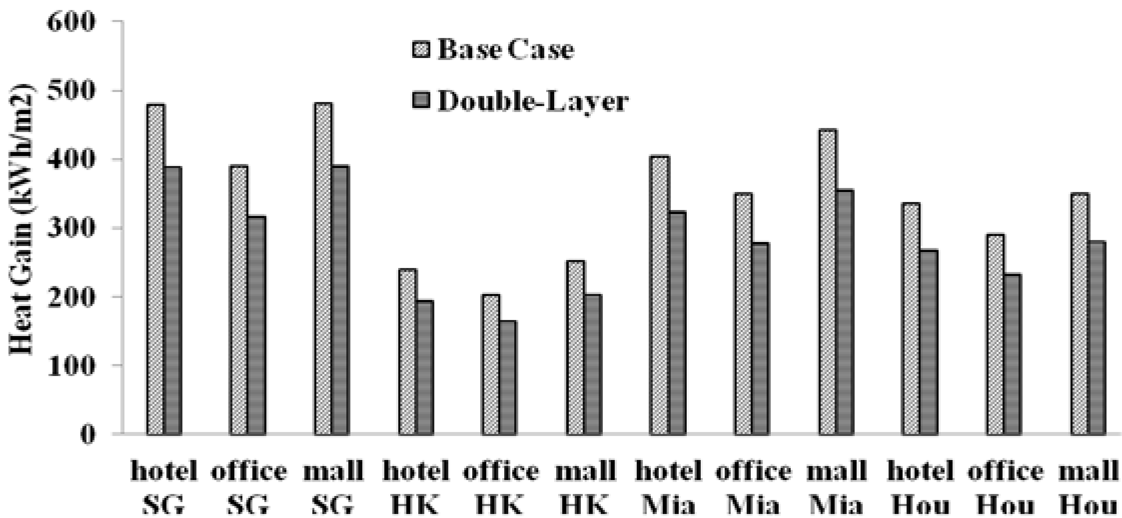
C3. Office in Miami (kWh/m^2) **D3. Office in Houston (kWh/m^2)**

	south	east	north	west		south	east	north	west
6mm	278.86	296.21	161.23	321.18	**6mm**	231.97	238.39	134.76	275.40
9mm	278.57	296.01	161.19	320.83	**9mm**	231.40	237.87	134.45	274.79
12mm	278.37	295.87	161.15	320.60	**12mm**	231.06	237.56	134.27	274.42

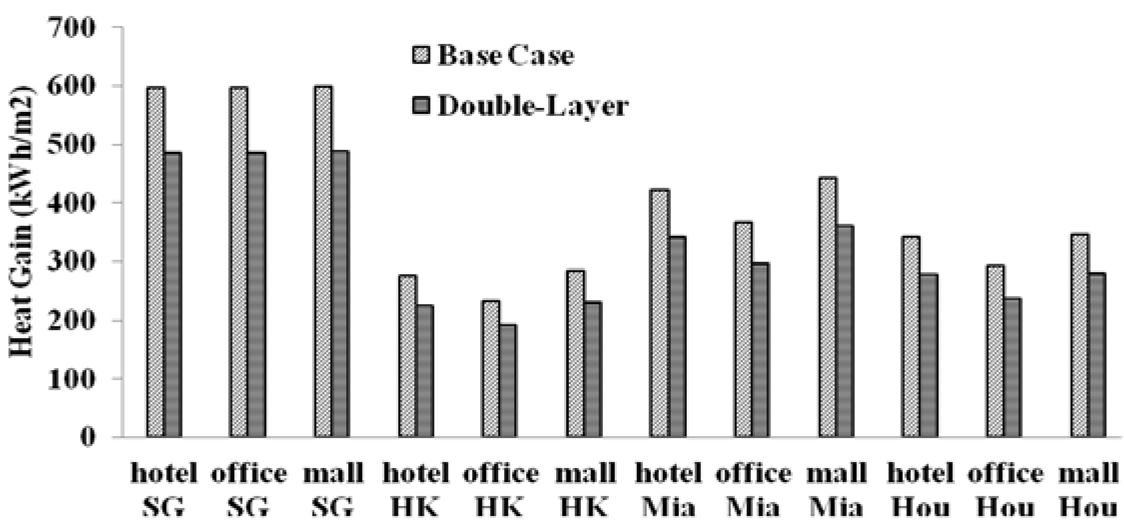
It is clear that increasing air layer thickness cannot improve the thermal performance of double-layer glazing. In cooling-dominant areas, increasing glazing's thermal resistance cannot help to reduce heat gain through window. During design and retrofitting of window surface, more attention should be paid on radiation blocking feature.

4.3.2 Performance of Double-Layer Glazing

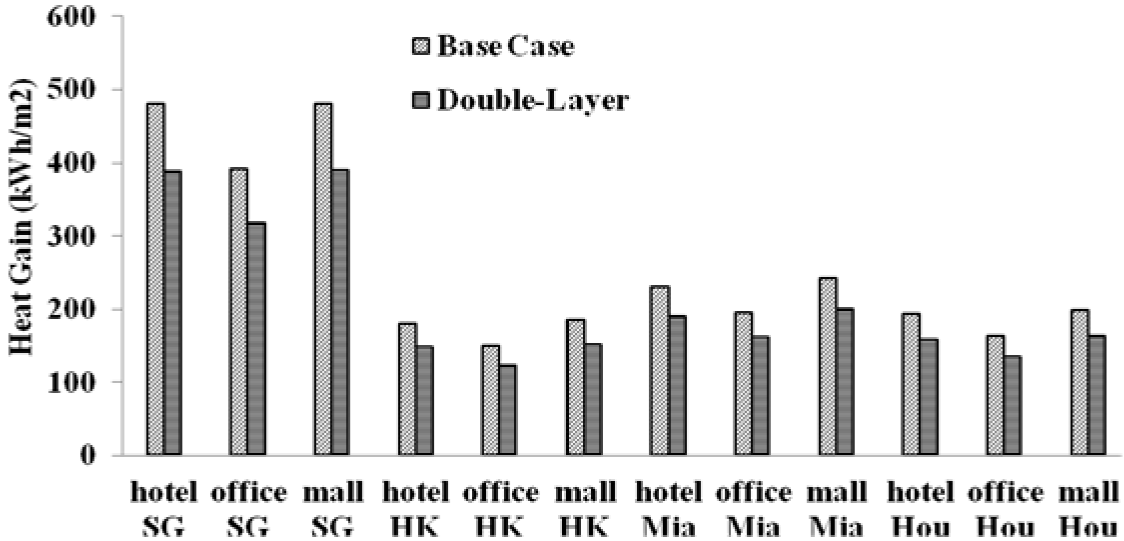
Due to its excellent thermal and acoustic insulation features, double-layer glass is widely applied in high latitude area where heating is necessary in winter. In cooling-dominant area with low latitude, single-layer glazing is the most widely applied window glass material. As mentioned before, in cooling-dominant area, window heat gain is mainly caused by transparent radiation. Double-layer glazing with high thermal resistance is often ignored. However, it cannot be granted that double-layer glazing is not applicable in cooling-dominant area. Figure 4.4 presents a comparison between heat gain through window area before and after double-layer application.



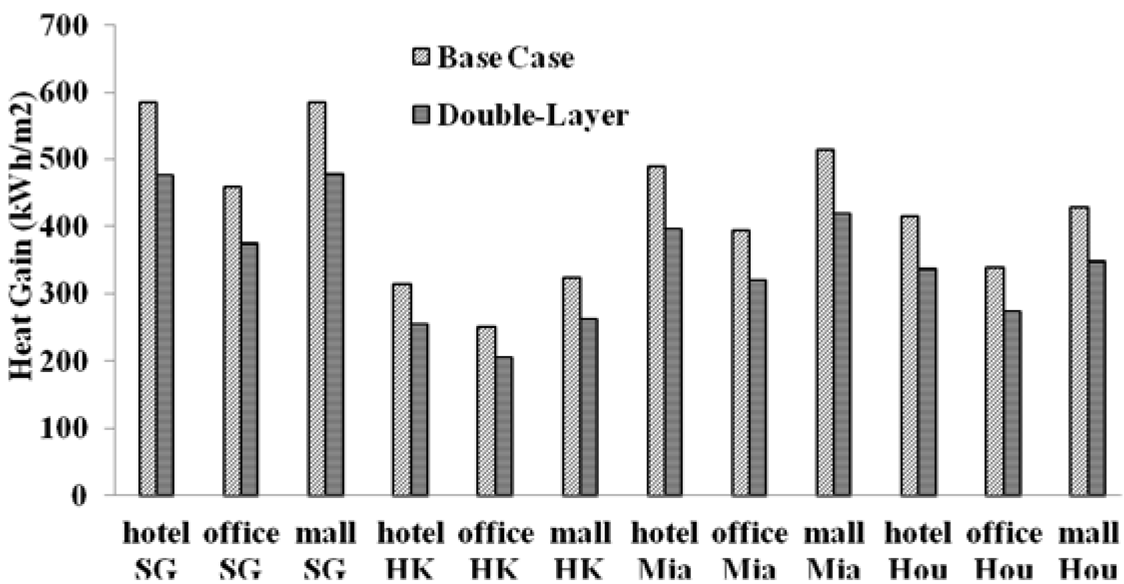
A. South orientation



B. East orientation



C. North orientation



D. West orientation

Figure 4. 4 Heat gain changes with the application of double-layer glazing

From Figure 4.4 it is clear that application of double-layer glazing in cooling-dominant area could also reduce heat gain through window area. In almost all cases, window heat gain is reduced by around 15% ~20%. The reason lies in the optical properties of the glass material. Table 4.6 gives the optical properties of the single-layer glass applied in base case.

Table 4. 6 Optical properties of single-layer glass applied in base case

Properties	data
Solar transmittance at normal incidence	0.70782
Front side solar reflectance at normal incidence	0.075
Back side solar reflectance at normal incidence	0.075
Visible transmittance at normal incidence	0.753
Front side visible reflectance at normal incidence	0.075
Back side visible reflectance at normal incidence	0.075
Infrared transmittance at normal incidence	0
Front side infrared reflectance at normal incidence	0.84
Back side infrared reflectance at normal incidence	0.84

Not all the solar radiation projected on glazing surface can travel through window area. Compared to single-layer glazing, double-layer glass has an extra glass layer which could help block out part of solar radiation. When radiation projected on the second glazing surface, part of it travels directly through, part of it is reflected back to the backside of the first glazing layer, and the rest of it is absorbed by the glazing material. Part of the absorbed radiation will be radiated into the room by long-wavedepth radiation. The reflected part of radiation will again be absorbed and reflected by the first glazing layer, and then repeats previous process. Therefore while introducing in the second glazing layer, what really matters is the “blocking” effect of glass material.

Although improving thermal resistance cannot help reduce solar heat gain, the blocking effect of glazing could help reduce unwanted solar radiation projection.

From Figure 4.4 it can also be concluded that though the proportion of heat gain reduction on different orientations does not vary significantly, gaps still exist in actual figure. In area like Singapore where north facing façade could also receive large amount of solar direct radiation, performance of double-layer glazing does not vary with orientations significantly. As latitude rises, heat gain reduction on north facing façade becomes less. Double-layer glazing performs better on east and west orientations. Also it is clear that hotel and shopping mall buildings receive more heat gain through window area than office buildings, application of double-layer glazing in hotel and shopping mall can achieve a larger reduction.

Application of double-layer glazing is not only necessary in high latitude area, but also effective in cooling-dominant area. During building design period, double-layer glazing should be considered as a practical alternative.

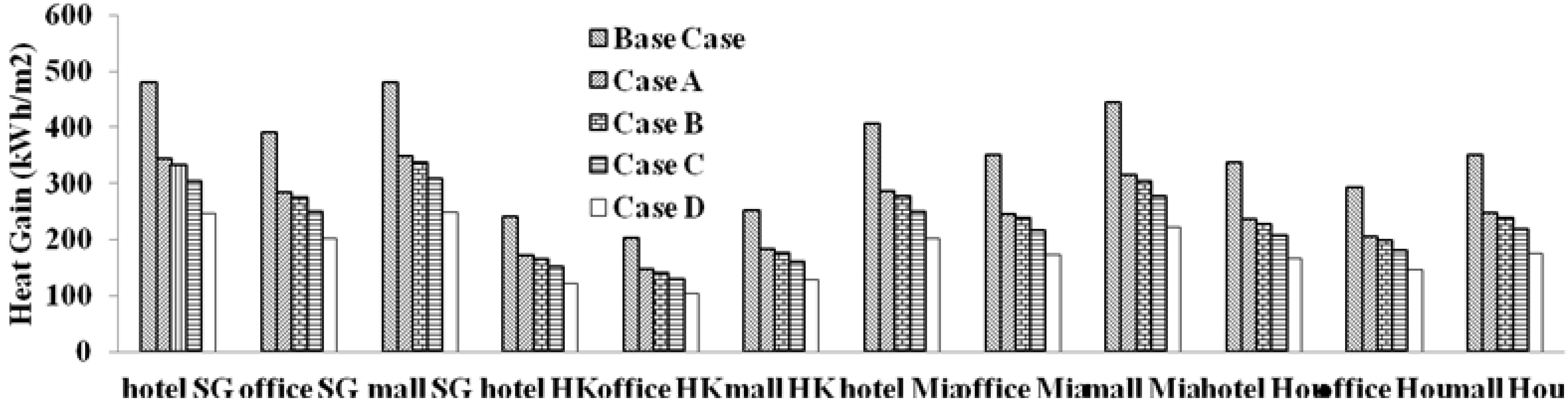
4.3.3 Performance of Low-E Glazing

Low-e glazing is short for low-emissivity glass. Low-e glass has a high transparency in the visible region and a high reflectance in the far-infrared region. A low-e coating is applied on one of the surfaces of the conventional double glazing, which is a film mainly formed by dielectric and metal. The coating has a high transparency in the visible region and a high reflectance in the far-infrared region, which can provide a comfortable visual environment while making a good insulation effect.

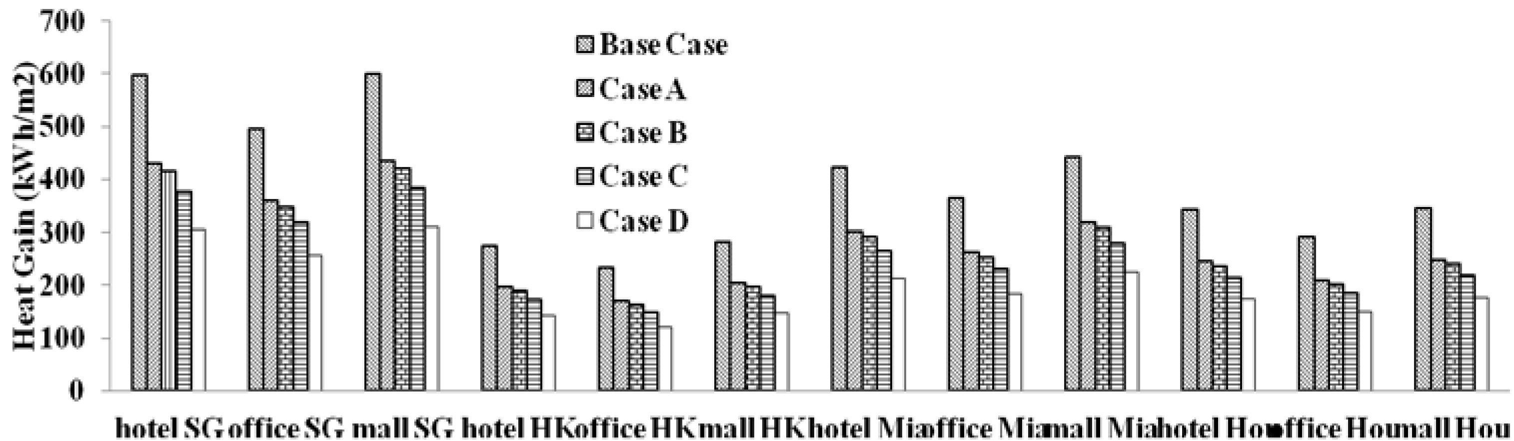
Low-e glazing has an excellent insulation feature, and is widely applied in high latitude area. In cooling dominant area the application of low-e glazing is quite limited until recent years. In this study, performance of low-e glazing in cooling dominant area is investigated. During simulation, four different types of low-e glass are selected. Their optical features are listed in Table 4.7.

Table 4. 7 Optical features of low-e glasses applied in simulation

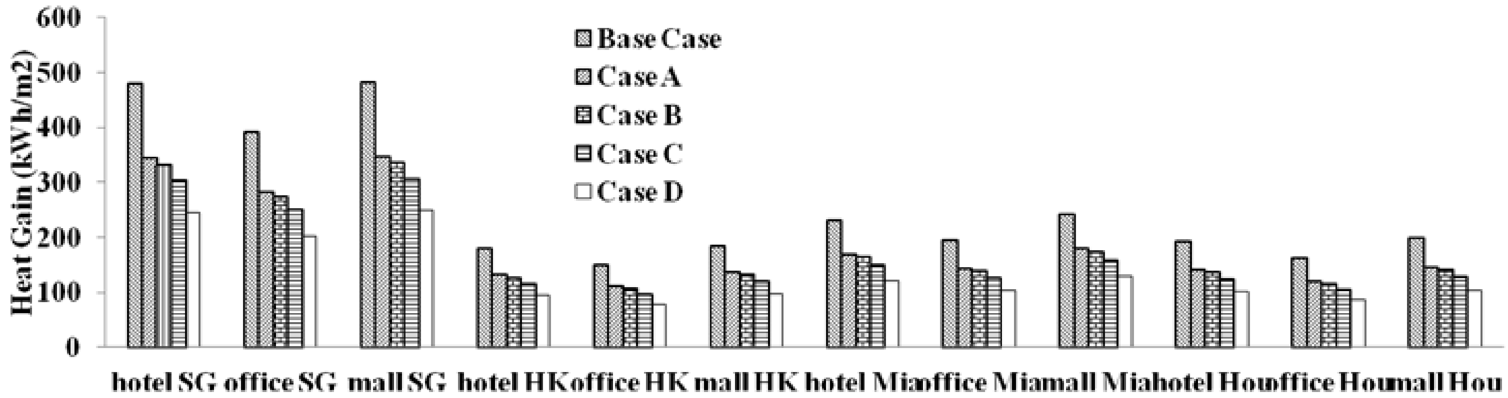
	Case A	Case B	Case C	Case D
Solar transmittance at normal incidence	0.598	0.591	0.555	0.4
Front side solar reflectance at normal incidence	0.074	0.144	0.280	0.281
Back side solar reflectance at normal incidence	0.109	0.199	0.180	0.403
Visible transmittance at normal incidence	0.805	0.803	0.853	0.742
Front side visible reflectance at normal incidence	0.087	0.068	0.059	0.064
Back side visible reflectance at normal incidence	0.096	0.062	0.079	0.052
Infrared transmittance at normal incidence	0	0	0	0
Front side infrared reflectance at normal incidence	0.84	0.84	0.84	0.84
Back side infrared reflectance at normal incidence	0.204	0.12	0.05	0.05



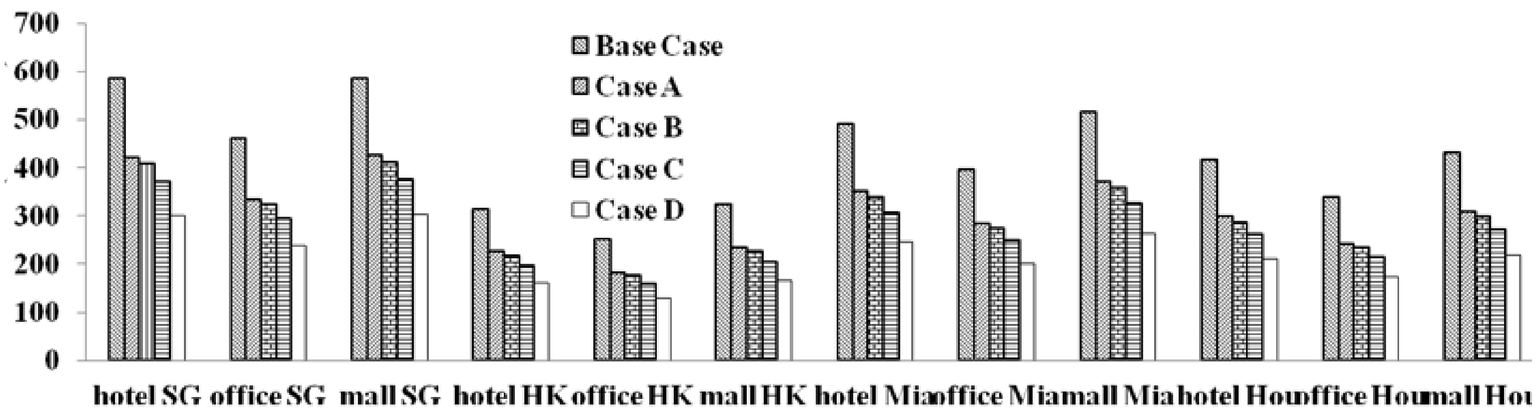
A. South Orientation



B. East Orientation



C. North Orientation



D. West Orientation

Figure 4. 5 Heat gain changes with the application of low-e glazing

Figure 4.5 presents the detailed heat gain reduction in four cases with the application of low-e glazing. Compared to Figure 4.4, it is clear that application of low-e glazing can further reduce window heat gain than double-layer glazing. The amount of reduction is proportional to the solar transmittance of the low-e glazing material.

4.3.4 Impact of Orientation

It can be concluded from Figure 4.4 and 4.5 that though the proportions of heat gain reduction on different orientations do not vary significantly, gaps still exist in actual figures. In area like Singapore where north facing façade could also receive large amount of solar direct radiation, performance of energy-efficient glazing materials like double-layer glass and low-e glass does not vary with orientations significantly. While latitude rises, heat gain reduction on north facing façade is getting less. Energy-efficient glazing can achieve a higher heat gain reduction on east and west orientations. Also it is clear that hotel and shopping mall receive more heat gain through window area than office buildings, double-layer glazing performs better in hotel and shopping mall.

In order to better quantify the cost-effectiveness of energy-efficient glazing material, low-e glazing with a solar transmittance of 0.4 is selected as an example. Heat gain reduction after installation of the low-e glazing on office building façade facing different orientations in four cities and their proportions in the total envelope surface heat gain are compared in Table 4.8. W (kWh) represents the annual heat gain through window area. G (kWh) stands for the annual heat gain through building façade. M (kWh) is the annual heat gain reduction from low-e glazing application.

Two variables, namely δ and γ are defined to make the discussion easier:

$$\delta = \frac{M}{W} \times 100\% \tag{4.15}$$

$$\gamma = \frac{M}{G} \times 100\% \tag{4.16}$$

In Singapore, heat gain on each façade does not vary much. Low-e glazing on east and west facades contributes about 20% more reduction to the total heat gain of the building than south and north orientations. Low-e glazing on south façade contributes the least. In Hong Kong, low-e glazing on west façade contributes the most reduction of solar heat gain, while low-e glazing on north façade contributes the least. It is also clear that in Hong Kong, performance of low-e glazing on different orientations differs from each other significantly. When it comes to Houston and Miami, performance of low-e glazing on north façade drops to around half of glazing facing other orientation.

Table 4. 8 Effects of energy-efficient low-e glazing material on office envelope heat gain on different orientations ($\delta = \frac{M}{W} \times 100\%$, $\gamma = \frac{M}{G} \times 100\%$)

A. Singapore

Orientation	M(kWh)	δ	γ
South	484,586	11.6%	10.1%
East	615,952	14.7%	12.7%
North	485,540	11.8%	10.0%
West	571,504	13.6%	11.6%
Total saving	2,157,582	51.7%	44.4%

B. Hong Kong

Orientation	M(kWh)	δ	γ
South	248,462	12.3%	10.1%
East	290,100	14.3%	12.1%
North	189,964	9.4%	8.0%
West	311,273	15.5%	13.0%
Total saving	1,039,795	51.5%	42.9%

C. Miami

Orientation	M(kWh)	δ	γ
South	416,319	13.2%	12.1%
East	443,908	14.1%	12.9%
North	247,777	7.6%	7.2%
West	481,484	15.3%	13.9%
Total saving	1,589,487	50.5%	46.3%

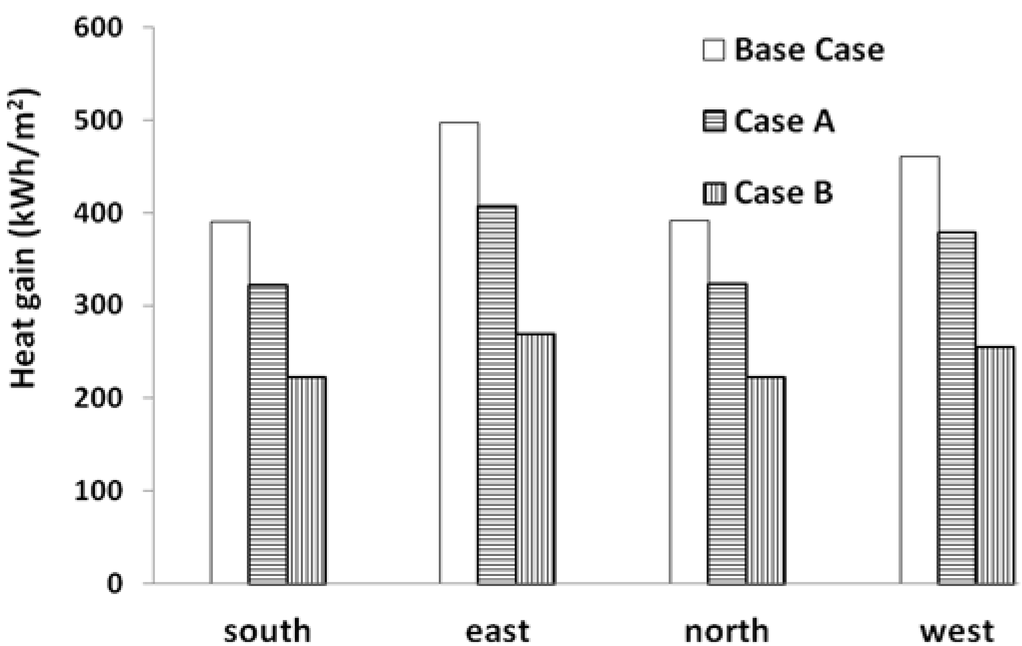
D. Houston

Orientation	M(kWh)	δ	γ
South	349,151	13.4%	11.9%
East	360,146	13.8%	12.4%
North	207,162	8.0%	6.9%
West	414,414	15.8%	14.1%
Total saving	1,330,872	50.9%	45.4%

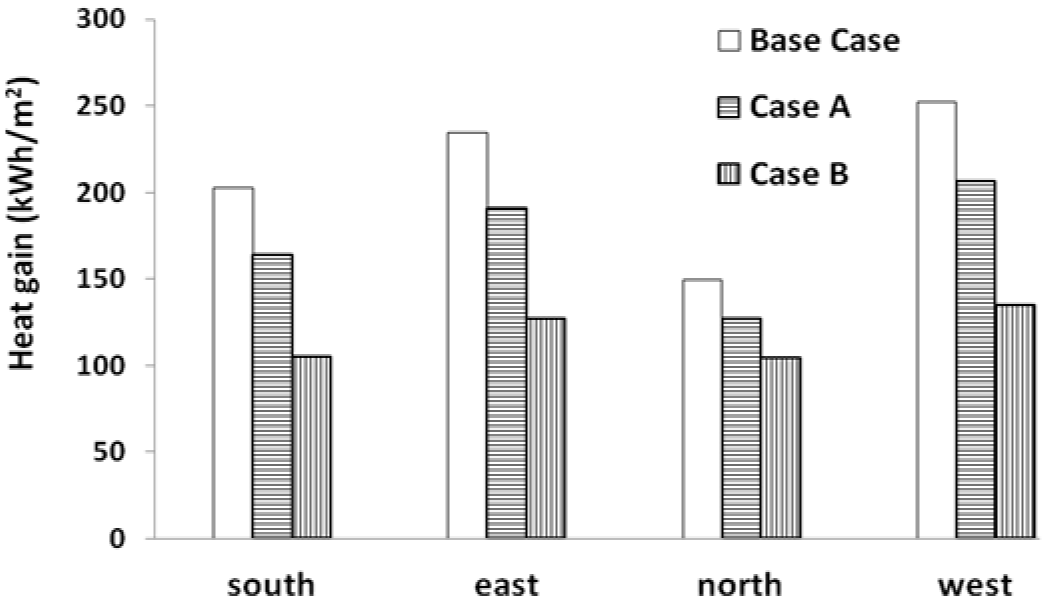
4.4 Shading Devices on Window Area

4.4.1 Annual Energy Performance

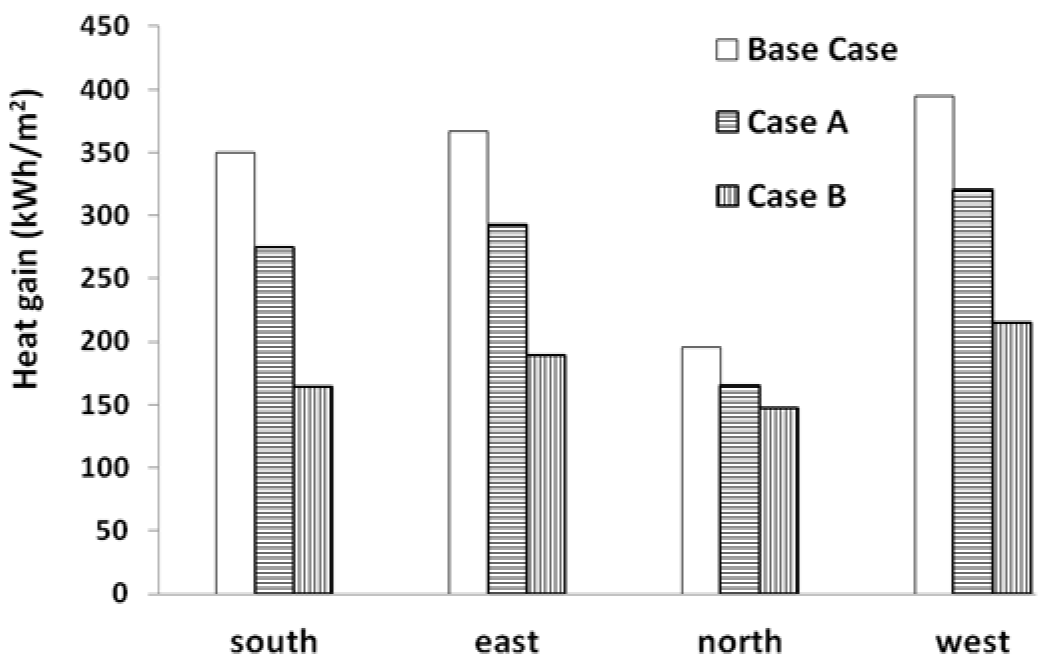
The annual total heat gain through window area of each orientation is presented in Figure 4.6. The Base Case stands for original window glazing without any shading devices. Case A stands for interior blind application on window area. Case B stands for overhang shading application on window area. The width of the blind is 0.025m. The reflectivity of the blind is 0.8. The position of the blind louvers is full open (tilt angle 90 °). The depth of overhang is 1m. The material of overhang is the same as building external surface. It should be noted that in the following discussion heat gain result is converted into heat gain per unit area of window glazing surface. The reason of this conversion is to reduce the impact of building shape, so that the result can serve as general reference for building design.



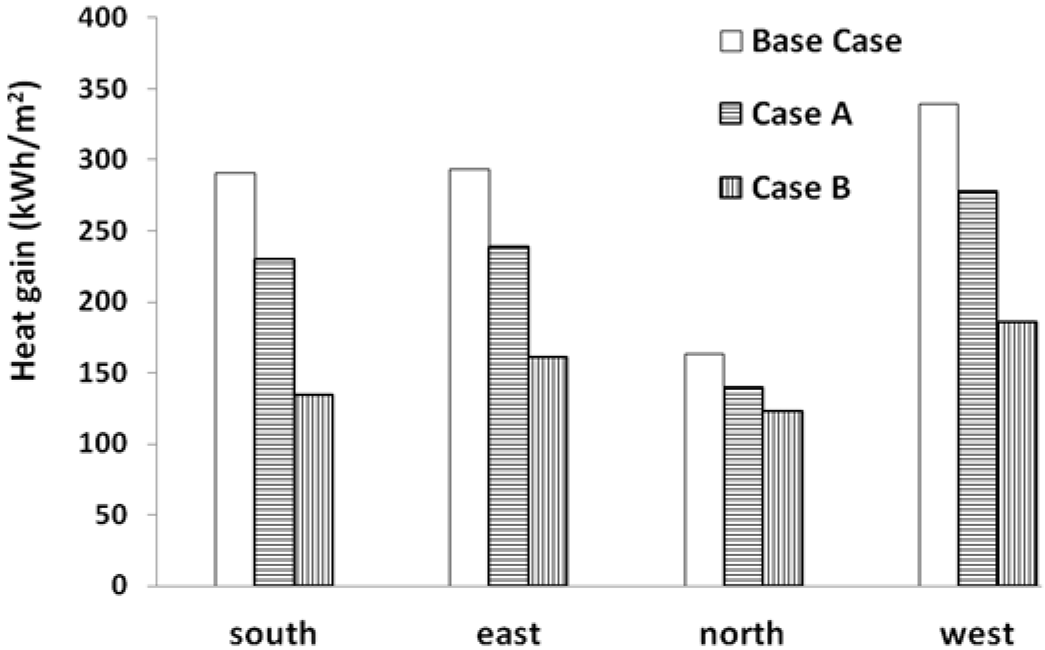
1. Singapore



2. Hong Kong



3. Miami



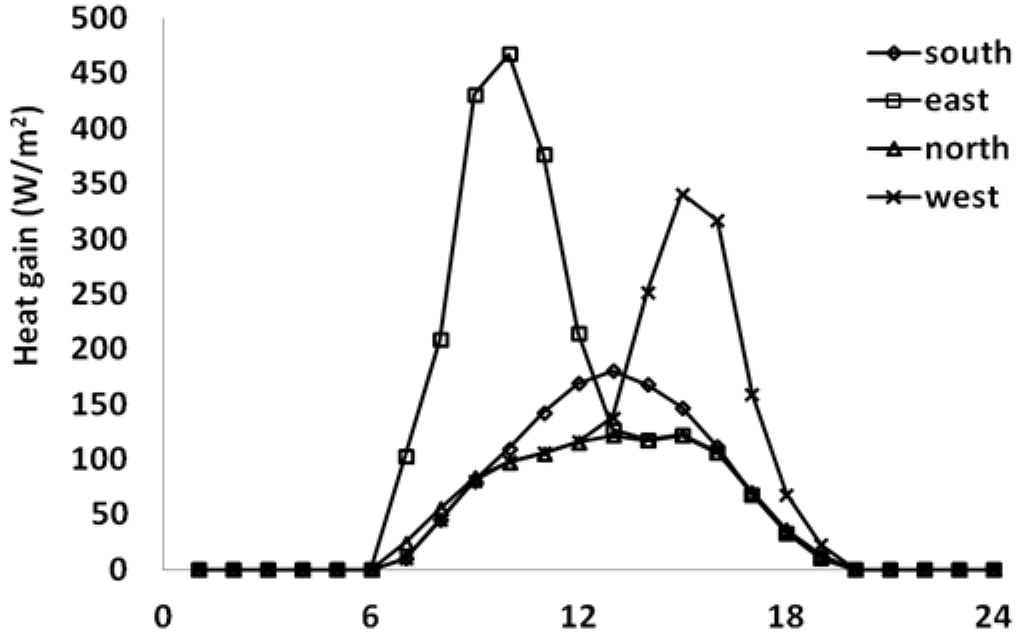
4. Houston

Figure 4. 6 Annual energy performances of shading design

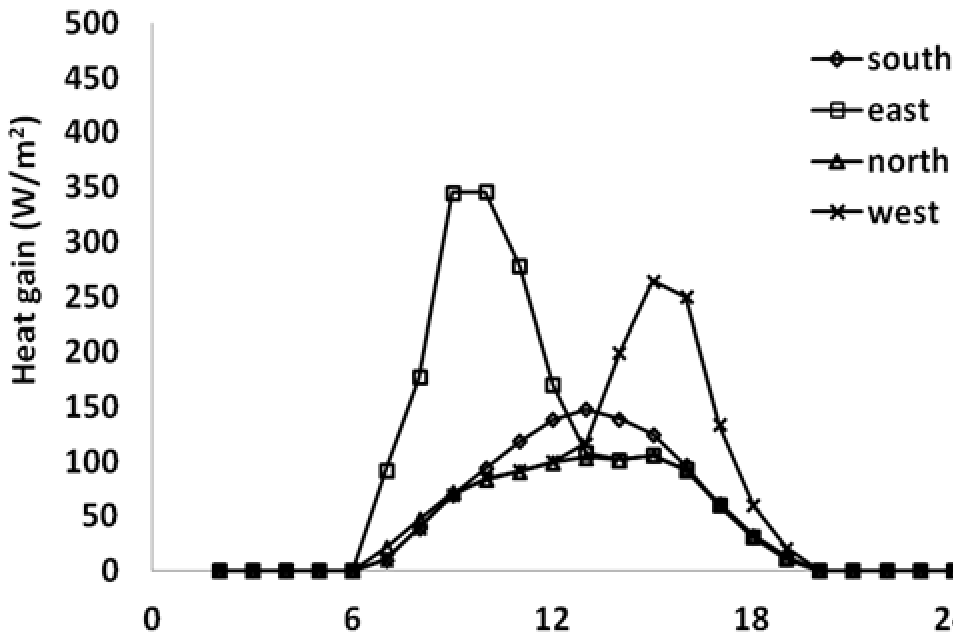
Window area serves as a connection between indoor and outdoor environment. Window can provide occupant with a pleasant working mood which is considered important in commercial high-rise building. However, according to our earlier research, heat gain through window area accounts for a large proportion in the overall building envelope heat gain (Huang et al., 2013). The balance between sight and energy efficiency should be considered very carefully before design and retrofitting of the building. Interior blind and overhang shading could reduce considerable amount of heat gain and retain view sight, thus become popular in office building retrofitting.

From Figure 4.6 it is clear that introducing in shading devices on window area will significantly reduce cooling load caused by solar radiation. In most cases, application of interior blind can reduce at least 20% heat gain through window glazing. Application of overhang can even reduce about 40% to 45% of the heat gain through window. It should be noticed that in the discussion, the blind louvers is full open. Under this situation, the shading effect of blind is the weakest. Even in its weakest status, the performance of blind is quite acceptable, which indicates that interior shading could also serve as a practical consideration in shading retrofitting in buildings.

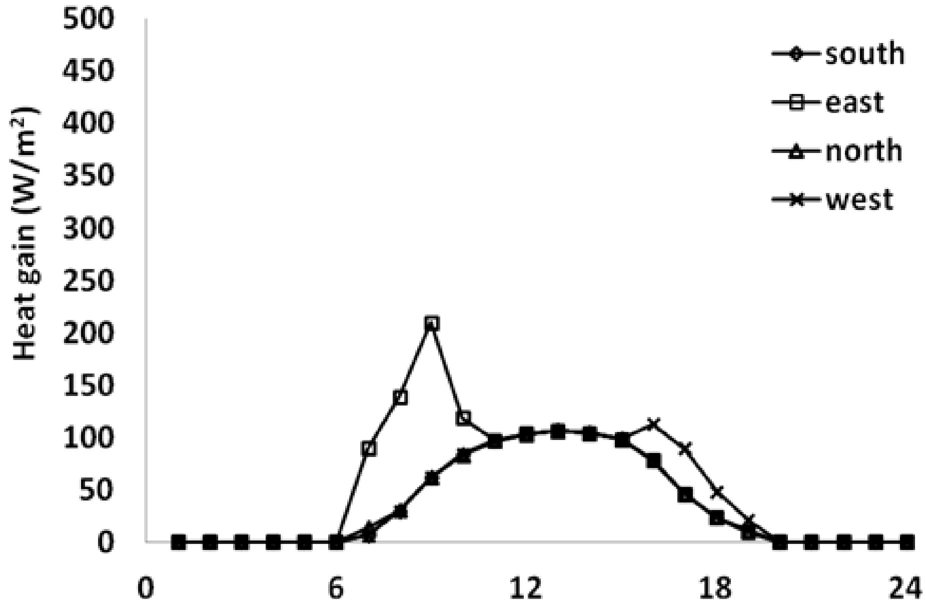
Another way of assessing the performance of shading devices is the reduction of peak cooling load. Figure 4.7 and Figure 4.8 present detailed heat gain reduction within a typical summer day due to shading design in Hong Kong and Houston. Reduction of peak cooling load could help reduce investment of AC system equipment and improve system operating efficiency. From above figures it is obvious that the application of shading devices can reduce peak cooling load significantly.



1. Base case

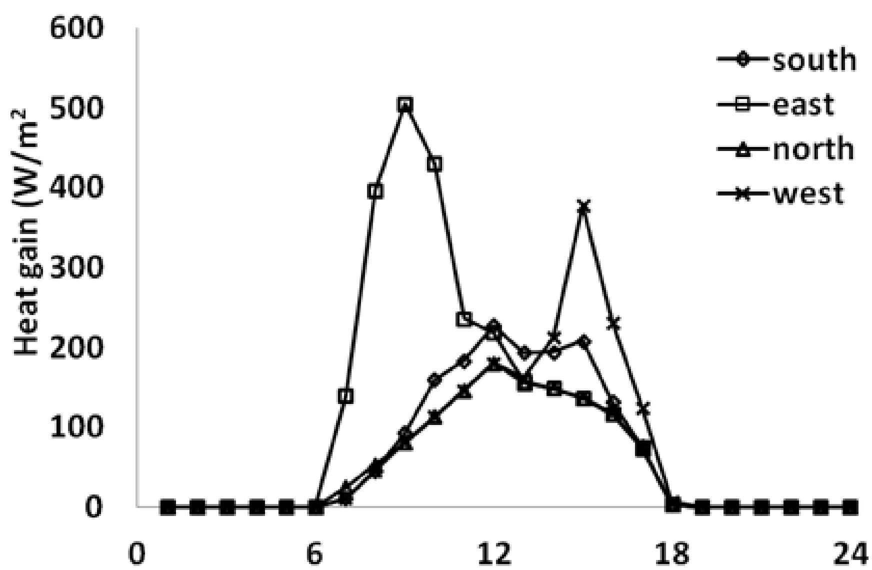


2. Case A

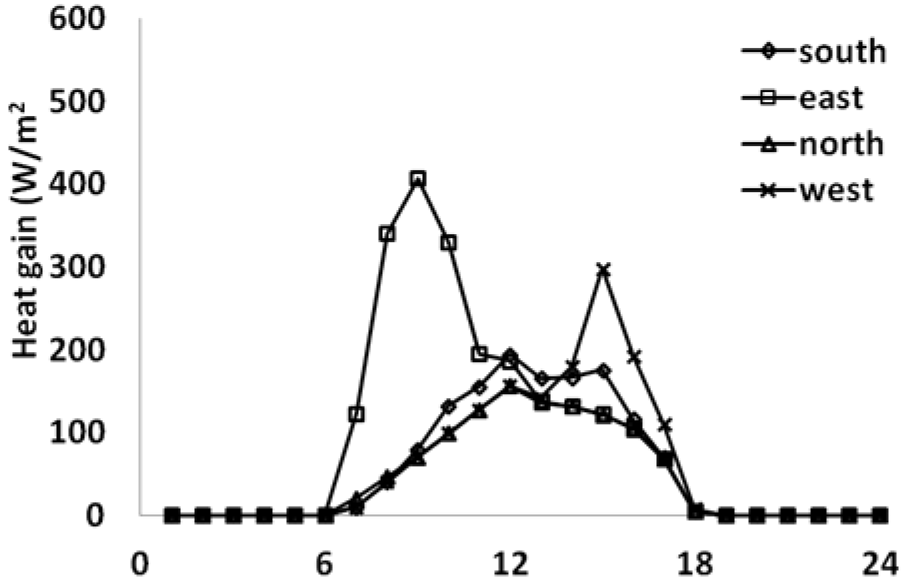


3. Case B

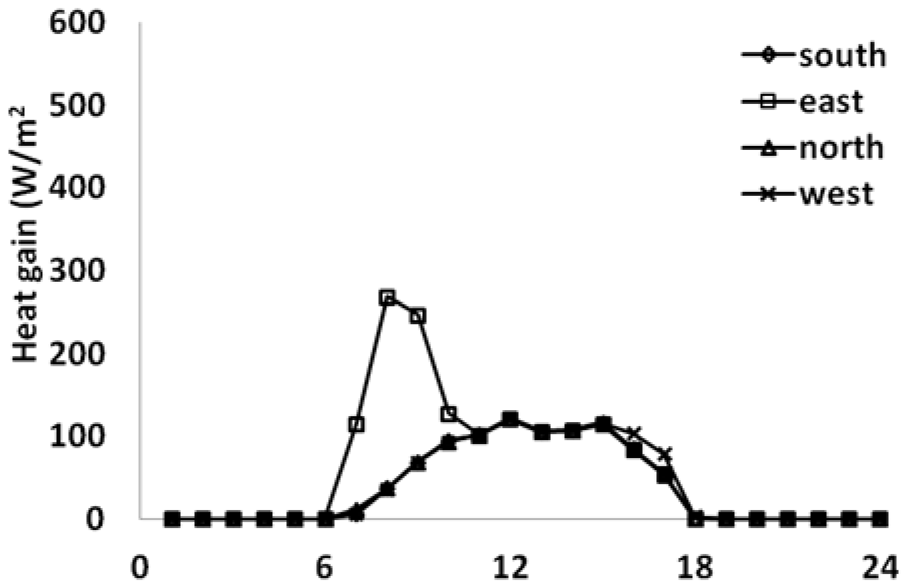
Figure 4. 7 Heat gain within a typical summer day in Hong Kong



1. Base Case



2. Case A



3. Case B

Figure 4. 8 Heat gain within a typical summer day in Houston

4.4.2 Impacts of Orientation and Geography Location

The effects of shading devices depend largely on the ability of blocking out direct solar radiation projected on window surface. Both orientation and geography location can affect the amount of direct solar radiation, thus their affects on shading device are discussed together in the study. In order to better quantify the cost-effectiveness of shading devices, heat gain reduction of shading devices on building façade facing different orientations in four cities and their proportions in the total envelope surface heat gain are compared in Table 4.9. W (kWh) represents the annual heat gain through window area. G (kWh) stands for the annual heat gain through building façade. M (kWh) is the annual heat gain reduction through shading retrofit.

Table 4. 9 Effects of shading device on heat gain of the envelope on different orientations ($\delta = \frac{M}{W} \times 100\%$, $\gamma = \frac{M}{G} \times 100\%$)

1. Singapore

Orientation	Case A			Case B		
	m(kWh)	δ	γ	m(kWh)	δ	γ
South	162,845	3.9%	3.4%	400,516	9.6%	8.3%
East	218,155	5.2%	4.5%	549,131	13.1%	11.3%
North	165,252	4%	3.4%	405,652	9.7%	8.4%
West	196,918	4.7%	4%	491,024	11.8%	10.1%
Total saving	743,170	17.8%	15.3%	1,846,324	44.2%	38%

2. Hong Kong

Orientation	Case A			Case B		
	m(kWh)	δ	γ	m(kWh)	δ	γ
South	92,694	4.6%	3.8%	234,806	11.7%	9.7%

East	103,482	5.1%	4.3%	256,976	12.8%	10.6%
North	54,556	2.7%	2.3%	108,708	5.4%	4.5%
West	110,516	5.5%	4.6%	281,881	14%	11.6%
Total saving	361,248	17.9%	14.9%	882,373	43.8%	36.5%

3. Miami

Orientation	Case A			Case B		
	m(kWh)	δ	γ	m(kWh)	δ	γ
South	179,526	5.7%	5.2%	444,455	14.2%	12.9%
East	175,699	5.6%	5.1%	426,027	13.6%	12.4%
North	72,122	2.2%	2.1%	115,456	3.7%	3.3%
West	179,792	5.7%	5.2%	431,147	13.7%	12.6%
Total saving	607,140	19.3%	17.7%	1,417,088	45.2%	41.3%

4. Houston

Orientation	Case A			Case B		
	m(kWh)	δ	γ	m(kWh)	δ	γ
South	146,437	5.6%	5%	375,747	14.4%	12.8%
East	130,492	5%	4.5%	316,064	12.1%	10.8%
North	56,978	2.2%	1.9%	97,426	3.7%	3.3%
West	147,206	5.6%	5%	366,970	14%	12.5%
Total saving	481,113	18.4%	16.4%	1,156,208	44.3%	39.5%

In Singapore, heat gain on each façade does not vary a lot. Shading devices on east and west facades contribute about 20% more reduction to the total heat gain of the building than those on south and north orientations. Shading device on south façade reduces the least heat gain compared with those on other facades. In Hong Kong, shading devices on south façade contributes almost the same as those on east and west façades. North facing shading device reduces only less than half heat gain compared with devices facing other orientations. When it comes to Houston and Miami, performance of the device on north façade drops to only 1/3 of devices facing other orientations. In Hong Kong, Miami and Houston, there is no big gap between performances of two different shading devices on north façade, while on other orientations overhang performs more than two times better than interior blind.

80% of the human population live between 20 and 60 degree north latitude, and in this study the four cities selected are all located within this area. Among these four cities, performance of shading devices on east and west facades is very stable. In area with very low latitude, shading device facing south does not contribute as much as those on other orientations. But as the latitude rises, performance of south facing device would rapidly increase to become the most cost-effective. As the latitude rises, both overhang and interior blind perform poorly on north façade. Considering investment and construction difficulties, interior shading which is cheaper and more convenient could be applied on north façade within this area.

4.4.3 Impact of Occupant Behaviour on Blind

According to previous study, occupants do not adjust interior blind very often (Zhang & Barrett, 2012; Wymelenberg, 2012). They tend to set the blinds in certain positions based on long-term perceptions of sun light and sun heat, and then just leave them there. As we all know that the shading effect of blind is highly affected by tilt angle of blind louvers. In this study, the impact of occupant behaviour is investigated. Performance of interior blind with different tilt angle is simulated. Figure 4.9 below presents the definition of tilt angle used in the simulation. While blind is full open, the tilt angle is 90°, the shading effect is the weakest. Figure 4.10 gives a comparison of interior blind performance with different louver tilt angles.

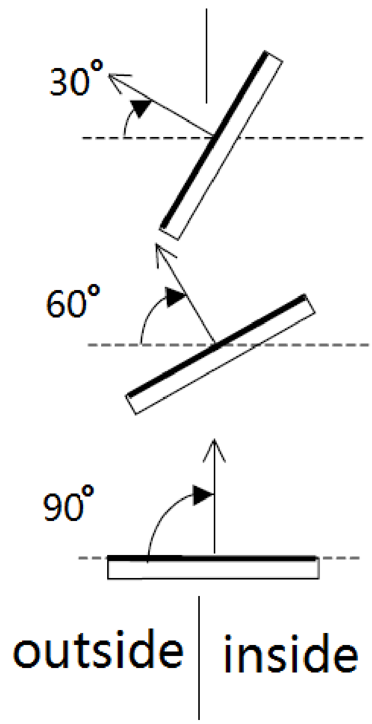
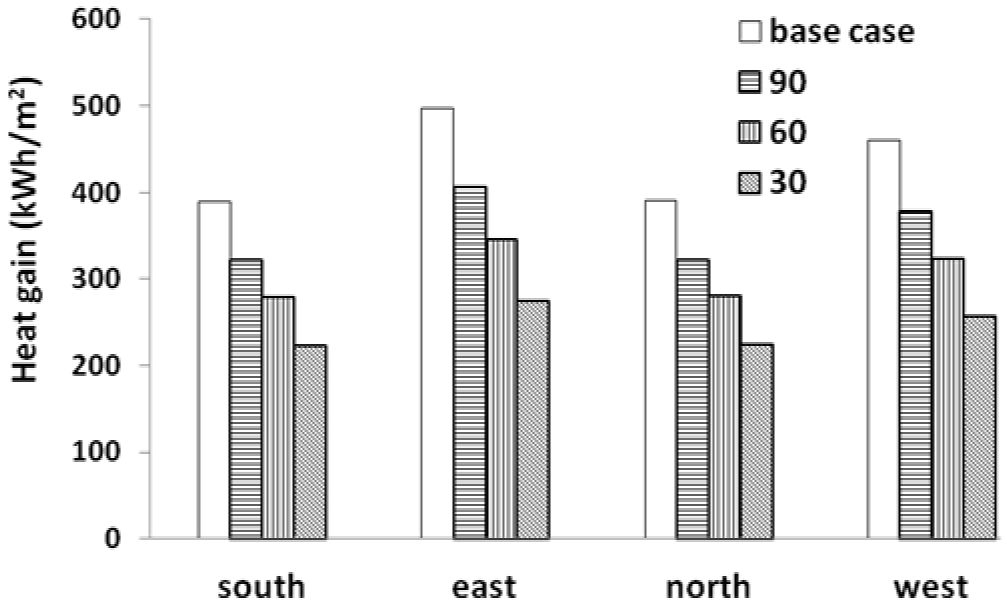
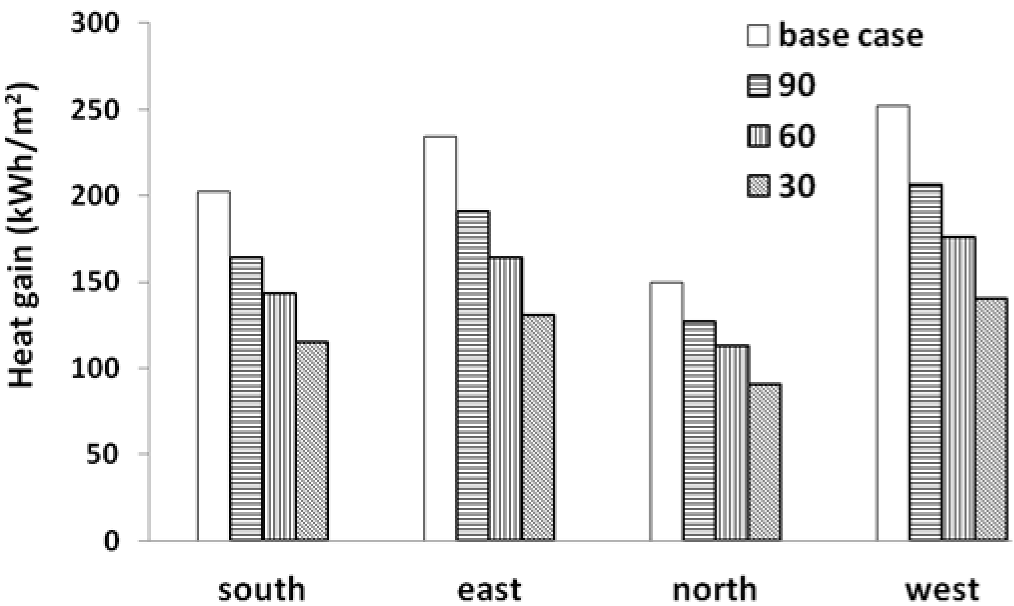


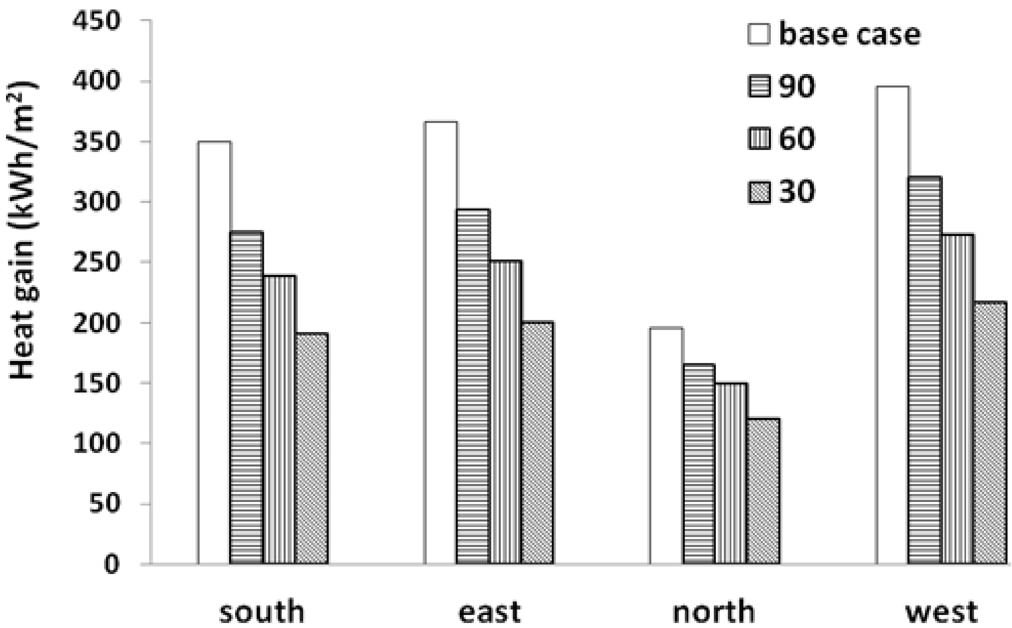
Figure 4. 9 Definition of blind tilt angle



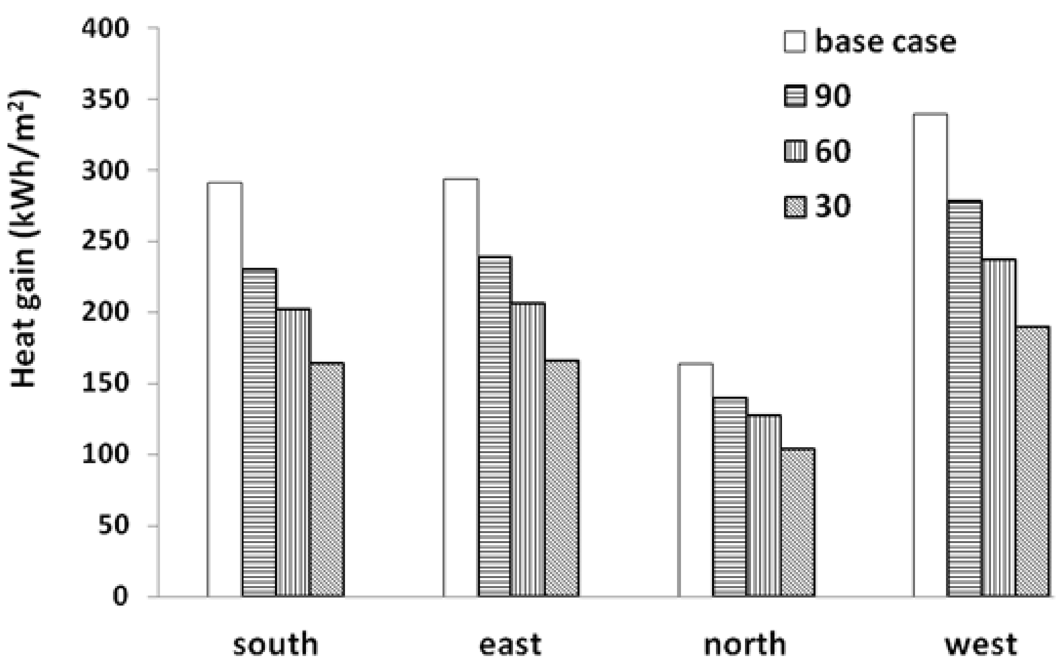
1. Singapore



2. Hong Kong



3. Miami



4. Houston

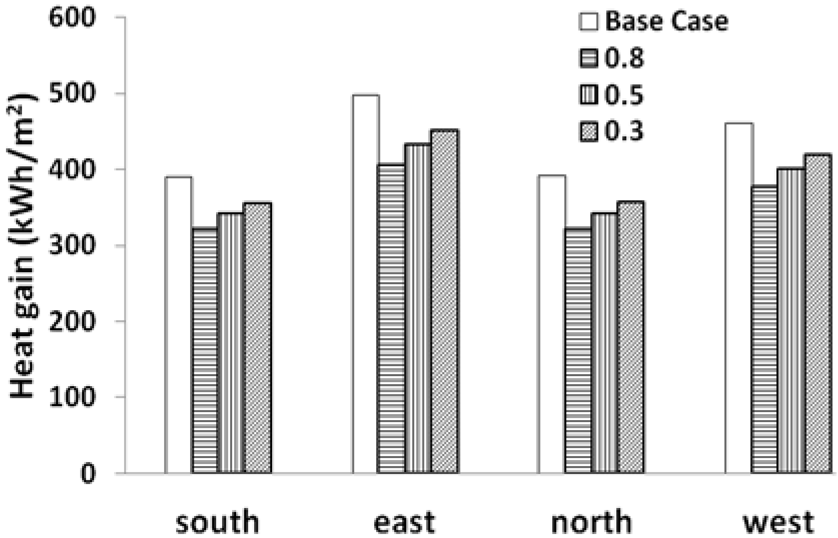
Figure 4. 10 Effect of tilt angle on blind performance

From above figure it is clear that the influence of louver tilt angle on blind shading effect is quite significantly. In most cases, setting the slat angle at 90°can only reduce window heat gain by about 15% to 20%, while setting the slat angle at 30°can achieve a reduction of around 40% to 50%. In some cases, performance of blind with a slat angle of 30°can even be better than that of overhang. It can be concluded that as the slat angle decreases, the performance of blind will be even better.

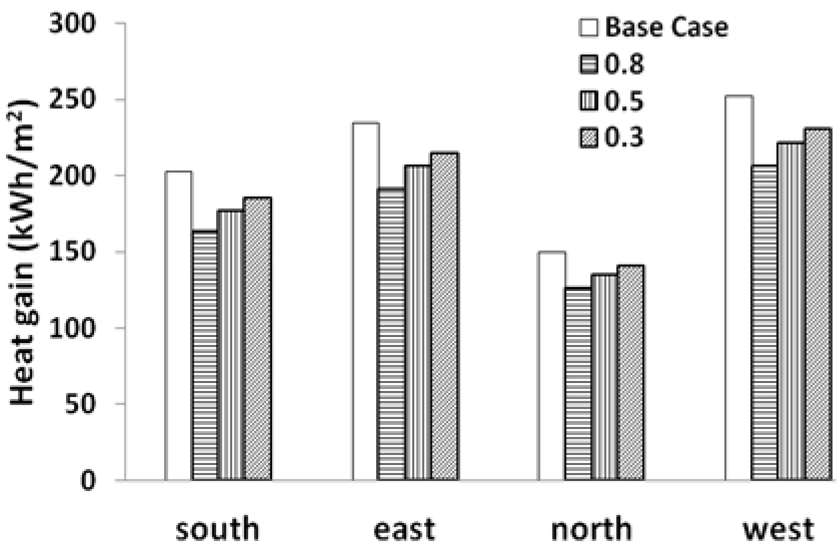
As mentioned above, a very important function of window is providing occupants with a pleasant indoor visual environment. The flexibility of blind makes it possible for the occupants to adjust the indoor environment themselves. By adjusting the louver tilt angle, the occupant can get a balance between thermal and visual comfort, which is quite important to the efficiency of office work. Besides, compared with exterior shading devices, interior blind is cheaper in price, and also simpler in installation, which makes it an acceptable alternation for shading design and retrofitting in buildings.

4.4.4. Impact of Reflectivity on Blind

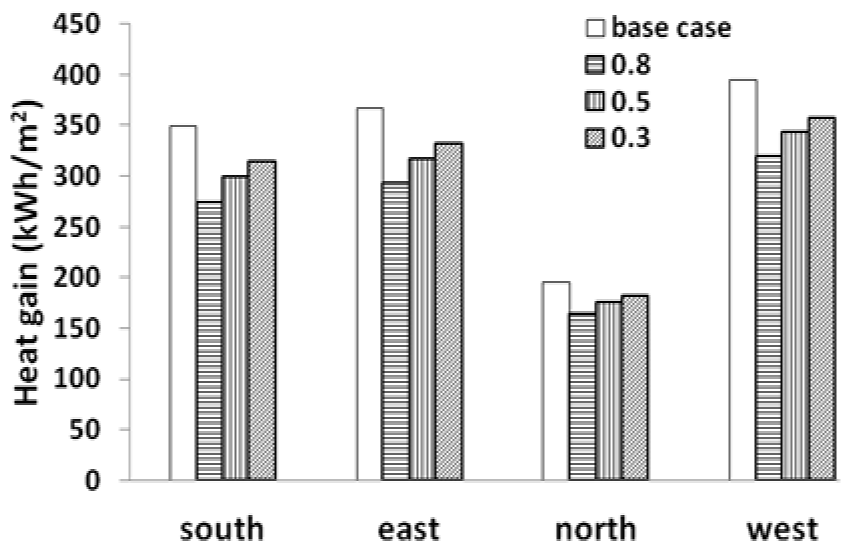
There are a number of parameters that can affect the reflectivity of blind, such as colour, material, and surface smoothness. The reflectivity of blind will decrease as operating period gets longer. Figure 4.11 presents the performance of interior blinds with different reflectivity. The tilt angle of blind louvers is 90°.



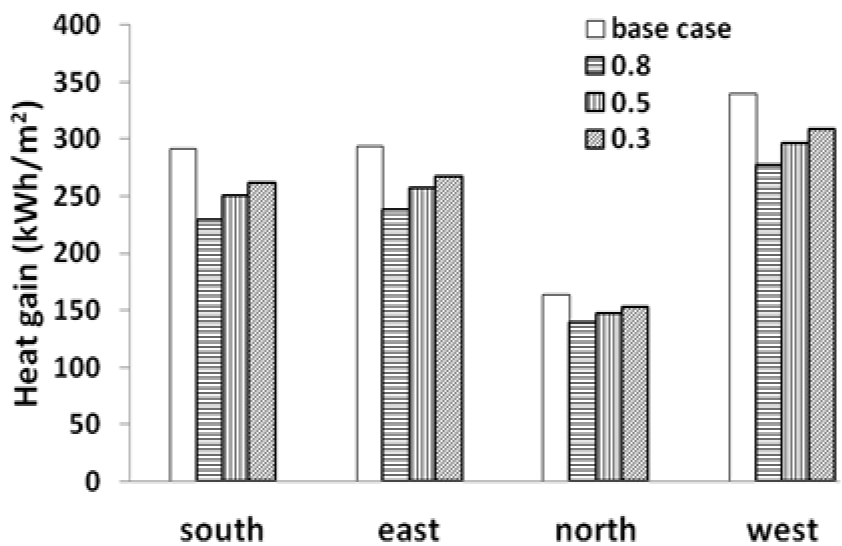
1. Singapore



2. Hong Kong



3. Miami



4. Houston

Figure 4. 11 Performance of blinds with different reflectivity

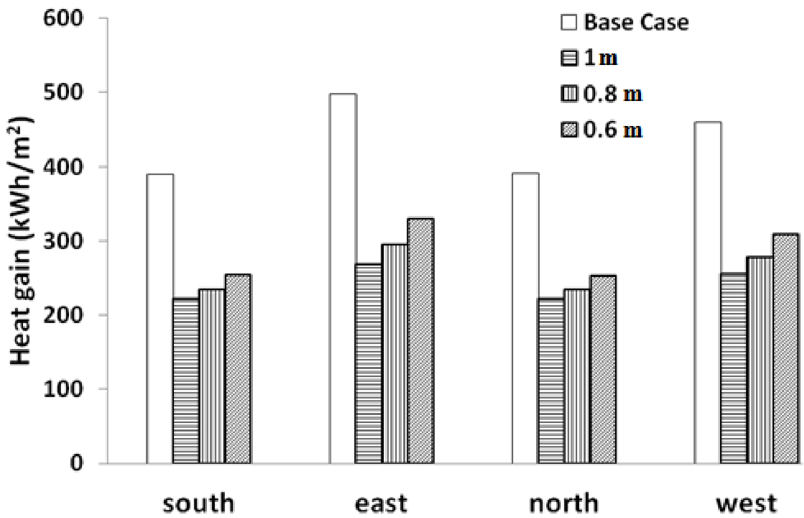
With the decreasing of reflectivity, the performance of blind drop seriously. When the reflectivity decreases to 0.3, the performance of blind reduces by more than half. Same conclusions could be achieved from result in other cities. Due to depth limitations only result of Hong Kong is reported here.

The reflectivity of blind has huge impacts on the performance of blind. During design period, high reflectivity blind should be selected. During daily operation, blind surface should be cleaned regularly so that material reflectivity can be retained longer. A regular replacement is also necessary.

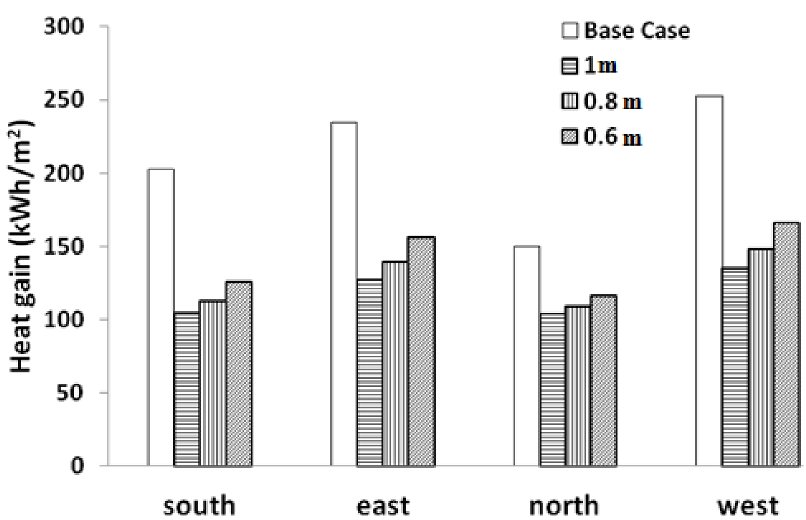
4.4.5. Impact of Overhang Depth

Figure 4.12 gives the performance of overhangs with different depth. It should be noted that the height of window in this study is 1.2m. It is clear that if overhang is longer than half of the window's height, the impact of depth on overhang performance is not that much. A reduction of 40% in depth only results in a drop of less than 20% in performance within all cases. It can be concluded that as the overhang depth decreases to less than half of window's height, the reduction in overhang performance is faster. It is also clear that in Singapore and Hong Kong, the impact of depth on overhangs facing east and west is larger than those facing north and south. While in Miami and Houston, impact of depth makes small difference among overhangs facing east, west and south.

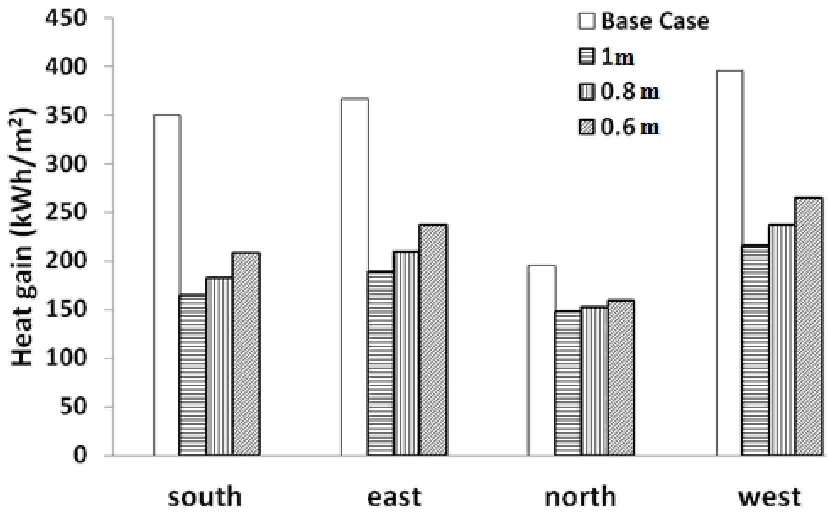
The performance of north facing overhang does not change a lot with overhang depth in all 4 cities.



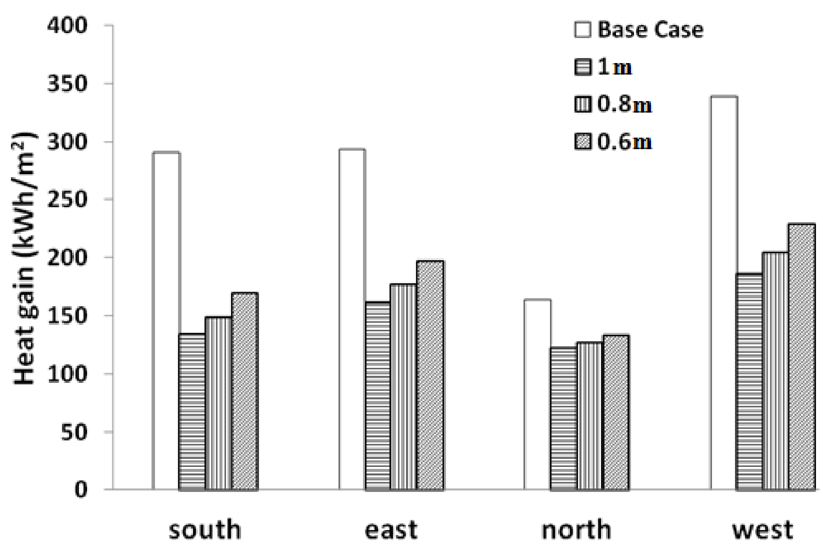
1. Singapore



2. Hong Kong



3. Miami



4. Houston

Figure 4. 12 Performance of overhangs with different depth

When the overhang depth is more than half of the window's height, the impact of overhang depth is not very significant. The impact of depth is higher on overhangs facing east and west, while overhang facing north is affected the least from overhang depth. In practical projects, overhangs facing east and west can be a little longer. When it comes to north façade, a short overhang or interior shading could be considered.

4.5 Summary

In this chapter, several popular energy-efficient designs on window area of commercial building envelope have been simulated and investigated. The effects of materials' optical and thermal feature are considered. The impacts of orientation and climate are also discussed.

Due to their excellent insulation performance, double-layer glazing and low-e glazing are widely applied in high latitude area where heating is required in winter. In cooling-dominant area, these glazing materials are often ignored in conventional building envelope design. This situation rises from the consideration that the majority of window heat gain is caused by solar radiation travelling through glazing. The insulation feature of window glazing has little influence on reduction of the window heat gain. However, the shading effect of double-layer glazing and low-e glazing could also help to block out unwanted solar radiation from getting inside the building. According to the simulation study, application of double-layer glazing could help to reduce about 15% ~ 20% of the total heat gain through window area. When it comes to low-e glazing with even lower solar transmittance, the performance can be better (around 50%).

Also, with the application of advanced glazing materials, the proportions of heat gain reduction on different orientations do not vary significantly. When it comes to actual figures, difference still exists. Glazing applied on east and west facing façade reduces more solar heat gain. Glazing applied on north facing façade only get an acceptable performance in low latitude area like Singapore where north façade can receive large amount of solar direct radiation.

In cooling-dominant climates, heat gain from window area plays an important role in building total cooling load. The application of interior blind and overhang could significantly reduce heat gain through window area throughout a year. Peak cooling load could also be greatly reduced. Besides, interior blind and overhang could retain the sight view of high-rise commercial building, which is a very important consideration in commercial building design and retrofitting.

Orientation and geography locations can affect the performance of shading devices largely. The amount of direct solar radiation projected on window surface is affected by both window orientation and the geography location of the building. During design and retrofitting process, device selection should be made very carefully to receive an optimal result. In cooling dominant climates not close to equator, though south facing windows could receive solar direct radiation all day round during most time of a year, the performance of shading devices on south façade does not vary a lot compared with those on east and west facades. In area close to equator, effect of north facing shading devices cannot be ignored. The performance of shading devices on east and west facades is very

stable among all cases. As the latitude rises, performance of interior and exterior shading devices on north façade makes small difference, but the application of shading devices on north façade still could make acceptable contribution on window heat gain reduction.
The tilt angle of blind louver has a strong impact on the performance of blind. If tilt angle is small enough, the heat gain reduction caused by interior blind can exceed that of overhang. Due to its price and flexible visual application, blind is considered to be a competitive measure in building envelope design and retrofitting.

The reflectivity of blind is another important factor that affects the performance. In order to maximize the shade effect, blind with high reflectivity is preferred. During daily operation, regular cleaning and replacement is necessary.

For overhang, the depth is considered to be an important parameter that influences the shade effect. When the overhang is longer than half of the window height, its impact on overhang performance is not very significant. For overhangs facing east and west, the impact of depth is relatively large. For overhang facing north, the impact of depth is little. As latitude rises, the impact of depth on south facing overhang increases.

Besides their thermal performance, blind and overhang shading devices could also affect the visual environment inside the building. Future work will focus on their daylighting performance and the energy-saving effect of devices facing different orientations in different geography locations.

Chapter 5

Case Study: Life Cycle Analysis of Overhang Retrofitting in Hong Kong

5.1 Introduction

Energy-efficient retrofitting of existing building is a huge contribution to the sustainability of the society since building energy consumption takes more than one fourth of total energy consumption. Of the total energy consumption from buildings, energy consumed by HVAC and lighting systems accounts for a large proportion, thus reducing energy consumed by these systems is a major issue concerned by building professionals and researchers. Solar shading design is a topic that draws worldwide attention in building energy design area. Proper shading design could cut down cooling load caused by external radiation and provide a comfortable indoor thermal and visual environment, which could reduce the energy consumption of air-conditioning and lighting. Moreover, building external structures are considered to be a good choice for installation of solar photovoltaic system, which could generate a considerable amount of electricity. Due to its multiple advantages, solar shading system has become a conventional item in existing building retrofitting as well as new building construction.

To determine whether an energy-effective system worth installation or not requires serious analysis and demonstration. During the assessment of energy-efficient retrofitting projects, apart from annual saving figures and economic payback time, energy and CO_2 emission payback periods should also be taken as indispensable references. Financial payback analysis and Life Cycle Assessment (LCA) are often adopted to assess whether a project cost-effective. The result may also greatly affect the policy making process of local construction industry, because sometimes the projects may be unacceptable based on economic consideration (especially in cases of retrofitting), but have considerable short energy and CO_2 emission payback periods. Life Cycle Assessment could be considered as an evaluation system to analyze every impact associated with a specific progress (energy and materials input as well as emissions to the environment from raw materials production, distribution, and utilization to maintenance, disposal and recycling), so that a full assessment on environmental, social as well as economic influences could be achieved, which could lead decision-makers to a more sensible decision.

In this chapter, a methodology is described for analyzing the energy and CO_2 emission payback periods of external overhang shading in a university campus in Hong Kong. Result shows that due to requirements of structural strength under typhoon situation, although introducing overhang shading system could reduce almost half of the cooling load in the related area, the energy and CO_2 emission payback periods of the project are still unrealistically long. This case study presents an example of multi-disciplinary approach being not only important to the energy-efficient retrofitting but also necessary for policy making in different climatic and geographic regions.

5.2 Literature Review and Research Methodology for Life Cycle Analysis

As early as 1982, Bekker (1982) raised an argument that using life cycle approach to analyze the consumption of energy and other resources in buildings and their impact on environment could be an appropriate method. Later, Adallberth (1997) proposed a method about calculation of life cycle energy consumption in buildings. Since then, a large number of researches and case studies on LCA of buildings have emerged.

Life cycle of a building could be divided into 2 main periods: the construction period (including materials production, installation) and operation period (including energy supply and management). During the period of construction, the energy consumption mainly comes from material acquisition and installation. Buchanan and Honey (1994) investigated the amount of energy required for building construction and the resulting CO_2 emissions to the atmosphere, and made a detailed list of embodied energy of a large amount of regular building materials, as well as CO_2 emission caused by their acquisition. Oka et al. (1993, 1995) quantified the total energy consumption and environmental pollution caused by building construction of different types, and gave a detailed breakdown of energy consumption and CO_2 emission in different purposes. González and Navarro (2006) carried out a case study in Spain, which showed that through selection of design and materials, a reduction of CO_2 emission of 27.28% could be achieved. After collecting and analyzing numerous research reports and case studies, Gustavsson, Joelsson, Ramesh et al. (2010A, 2010B), as well as Sharma et al. (2011) made comprehensive summaries on LCA in building constructions and pointed out that although situations may be different with the difference in structures and local productivities, embodied energy takes a smaller part (from 20% to 40%) in total energy consumption, and the impact of different stages of building construction on CO_2 emission is similar to that on energy consumption.

During operation period, professionals often turn to heat recovery ventilation system, air or ground/water source heat pumps, solar thermal collectors and building integrated solar photovoltaic panels to reduce the energy consumption. Lu and Yang (2010) summarized a large amount of literatures on LCA of building-integrated photovoltaic system and gave a detailed calculation on energy and CO_2 emission payback time of a roof-mounted grid-connected BIPV system. Saner et al. (2010) collected system data of geothermal heat pump systems from USA, Japan and Europe, and claimed that the application of GSHP system could reduce environmental impact by more than 50%, and this figure depended largely on the primary resource of the supplied electricity, while other technical factors only accounted for small fractions. Shah et al. (2008) examined the life cycle environmental impacts of three different heating and cooling systems in four different regions in USA and found that in most locations, heat pump system had the highest environmental impact comparing to warm-air furnace and hot water boiler coupled with air-conditioner, and the substitution of high-efficiency equipment did not affected the performance. They also found that the more renewable energy source was utilized, the better heat pump system performed. Gracia et al. (2010) evaluated the life cycle environmental impact of phase change materials in a Mediterranean building. They discovered that although application of PCM decreased the energy consumption during operation, it did not reduce the environmental impact a lot throughout the building's lifetime. For 100 years, the overall impact would only be reduced by about 10%.

Previous researches mainly focus on life cycle environmental impacts of the entire building or air-conditioning systems inside buildings. There are few researches concerning life cycle analysis of external shading systems. In this paper, a prediction and analysis system of energy and CO_2 emission payback periods calculation for external shading system is presented in detail. A specific case study is also described in order to display the impact of LCA approach on practical project. The case study involves an overhang shading retrofitting project on 5 buildings in the campus of The Hong Kong Polytechnic University. The details of the design and construction are listed in detail. The energy and CO_2 emission payback period calculation results are described. The paper also discusses the applicability of external shading system in different climatic and geographic regions and the value of this conclusion to local construction industry.

5.2.1 LCA Goal and System Boundary Definition

The goal of LCA is to assess the life cycle environmental impact of the external shading system on the global environment. External shading system includes supporting structures, shading platforms, as well as necessary attachments, sealants and protections. The life cycle of the system includes manufacturing of the materials, site preparation, transportation of equipment and materials, installation of shading system and attachment, system operation and disposal. It should be noticed that shading system could reduce the cooling load of the existing air-conditioning system in the building, and therefore reduce the energy consumption as well as CO_2 emission annually. However, installing extra shading system on existing structures requires investment of labor and materials, which are embodied with CO_2 emission and energy consumption in their manufactory, transportation and installation. According to above data, the energy and CO_2 emission payback periods could be calculated as follows:

$$T_{energy} = \frac{Q_l}{Q_o} \tag{5.1}$$

$$T_{CO_2} = \frac{M_l}{M_o} \tag{5.2}$$

Where T_{energy} (Y) and T_{CO_2} (Y) are payback time of energy and CO_2 emission, respectively, while Q_l (J) and M_l (kg-CO_2) are energy consumption and CO_2 emission due to construction of the system, respectively, Q_o (J) and M_o (kg-CO_2) are annual reduction of energy consumption and CO_2 emission due to system operation, respectively. With calculation result of T_{energy} and T_{CO_2}, the practicability of a shading system could be assessed.

5.2.2 Manufacture and Transportation of Materials

In order to calculate the amount of CO_2 emission as well as embodied energy of building materials, a list of required building materials should be prepared. Necessary information should be sorted, such as form, amount, manufacturer, raw material origin and details during manufactory progress of each material, distances between origins and manufacturers, distances between manufacturers and building locations. For a specific type of material, the CO_2 emission during its manufacturing could be expressed as follows:

$$M_m = \left(M_{\min e} + M_{tr} \cdot D_r + \sum_n M_s + M_{tp} \cdot D_p \right) \cdot M \tag{5.3}$$

Where M_m (kg-CO_2) stands for the total CO_2 emission during the manufacture of a specific material, M_{mine} (kg-CO_2/t) is CO_2 emission from mining of raw materials, M_{tr} (kg-CO_2/tkm) is CO_2 emission per tkm from transportation of raw materials from origin to manufacturer, M_s (kg-CO_2/t) is CO_2 emission from each step of end product preparation, M_{tp} (kg-CO_2/tkm) is CO_2 emission per tkm from transportation of end product from manufacturer to building location, D_r (km) is the distance between origin and manufacturer, D_p (km) is the distance between manufacturer and building location, and M (t) is the total quantity of the material needed. The embodied energy of a specific material could be expressed as follows:

$$Q_m = \left(Q_{mine} + Q_{tr} \cdot D_r + \sum_n Q_s + Q_{tp} \cdot D_p \right) \cdot M \tag{5.4}$$

Where Q_m (J) stands for the total energy consumed during the manufacture of a specific material, Q_{mine} (J/t) is energy consumption from mining of raw materials, Q_{tr} (J/tkm) is energy consumption per tkm from transportation of raw materials from origin to manufacturer, Q_s (J/t) is energy consumption from each step of end product preparation, Q_{tp} (J/tkm) is energy consumption per tkm from transportation of end product from manufacturer to building location, D_r (km) is the distance between origin and manufacturer, D_p (km) is the distance between manufacturer and building location, and M (t) is the total quantity of the material needed.

5.2.3 Installation of System and Supporting Attachment

Large amount of work is carried out at the construction site. Energy and water should be prepared for necessary transporting, welding and cooling. Transportation of equipment and workers should also be considered. However, due to the complexity and diversity of construction site work, it is very hard to get a systematical method to precisely estimate the energy consumption and CO_2 emission of a specific site construction. The most commonly used approach is to comprehensively monitor processes of construction works case by case and keep complete records. The accurate energy consumption and CO_2 emission could be sorted out from the statistic data after construction. Suzuki and Oka (1993, 1995, 1998) investigated large amount of different construction projects in Japan and listed detailed energy consumption and CO_2 emission from constructions of different types of buildings. In their research, buildings were categorized according to their structure and proportion of structural materials. Considering that shading system could be treated as shading platform supported by structural materials, data from building construction cases with similar structures are selected to predict the energy consumption and CO_2 emission in this paper. The energy consumption and CO_2 emission from the site construction could be expressed as follows:

$$Q_c = q_c \cdot A \tag{5.5}$$

$$M_c = m_c \cdot A \tag{5.6}$$

Where Q_c (J) and M_c (kg-CO_2) are the total amount of energy consumption and CO_2 emission from site construction of shading system, respectively, A (m^2) is the area of shading platforms, q_c (J/m^2) and m_c (kg-CO_2/m^2) are energy consumption and CO_2 emission per m^2 from site construction of shading system, respectively.

5.2.4 Energy Saving and CO_2 Reduction during System Operation Period

After installation of shading system, radiant heat gain through windows could be reduced. The ability of the shading system to intercept the direct solar radiation depends on the area of the shadow projected on the window glass. In area within the shadow zone the direct solar radiation is blocked out, while in area outside the shadow zone direct solar radiation still accounts for the total radiant heat gain. Meanwhile, the shading system itself also releases heat in the form of radiation, and part of the radiation heat will also be absorbed by the window glazing in the form of diffuse radiation. By comparing heat gain difference before and after the installation of shading system, performance of the shading system could be assessed.

5.2.5 System Maintenance

After the construction, the shading system may require routine maintenance to stay effective. The energy consumption and CO_2 emission from necessary cleaning, repair and revision could be expressed as follows:

$$Q_m = q_m \cdot A \tag{5.7}$$

$$M_m = m_m \cdot A \tag{5.8}$$

Where Q_m (J) and M_m (kg- CO_2) are total amount of energy consumption and CO_2 emission from system maintenance, respectively, q_m (J/m^2) and m_m (kg- CO_2/m^2) are energy consumption and CO_2 emission per m^2 from system maintenance, respectively, and A is area of the shading platform.

5.2.6 System Disposal

System disposal period includes demolition of shading system (including structure, platform and attachment) and transportation of materials to disposal plant. The energy consumption and CO2 emission from system disposal period could be expressed as follows:

$$Q_d = q_d \cdot A + q_{td} \cdot M \cdot D_d \tag{5.9}$$

$$M_d = m_d \cdot A + m_{td} \cdot M \cdot D_d \tag{5.10}$$

Where Q_d (J) and M_d (kg-CO_2) are total amount of energy consumption and CO_2 emission from system disposal, respectively, q_d (J/m^2) and m_d (kg-CO_2/m^2) are energy consumption and CO_2 emission per m^2 from system disposal, q_{td} (J/tkm) and m_{td} (kg-CO_2/tkm) are energy consumption and CO_2 emission per tkm due to transportation of demolished materials from building location to disposal plant, respectively, A (m^2) is area of the shading platform, M (t) is the total mass of demolished materials, and D_d (km) is distance between building location and disposal plant.

5.3 Results and Discussion

5.3.1 Case Information

The case study involves an exterior shading retrofitting project in a university campus in Hong Kong. In an earlier study, reduction of air-conditioning load by external shading was experimentally and numerically investigated (Wong & Niu, 2008). Three different types of shading devices (slat-type sunshade, overhang and solar film) were studied. Results showed that installation of shading device on building facades was an effective way to reduce cooling load caused by solar radiation heat gain. Shading device installed on west-façade made the most significant effect on reducing solar heat gain, followed by east-facing device with a slight disparity, while south-facing device made the least effect. Results also showed that the most efficient device was the slat-type sunshades, with which a reduction of up to 90% in heat gain could be achieved. And the least efficient device was the overhang; reducing only 30%~ 40% of the solar heat gains.

The Campus Development Office of the university decided to install exterior overhangs on the east and west facades of five existing buildings. Figure 5.1 gives details about the buildings' locations and orientations.

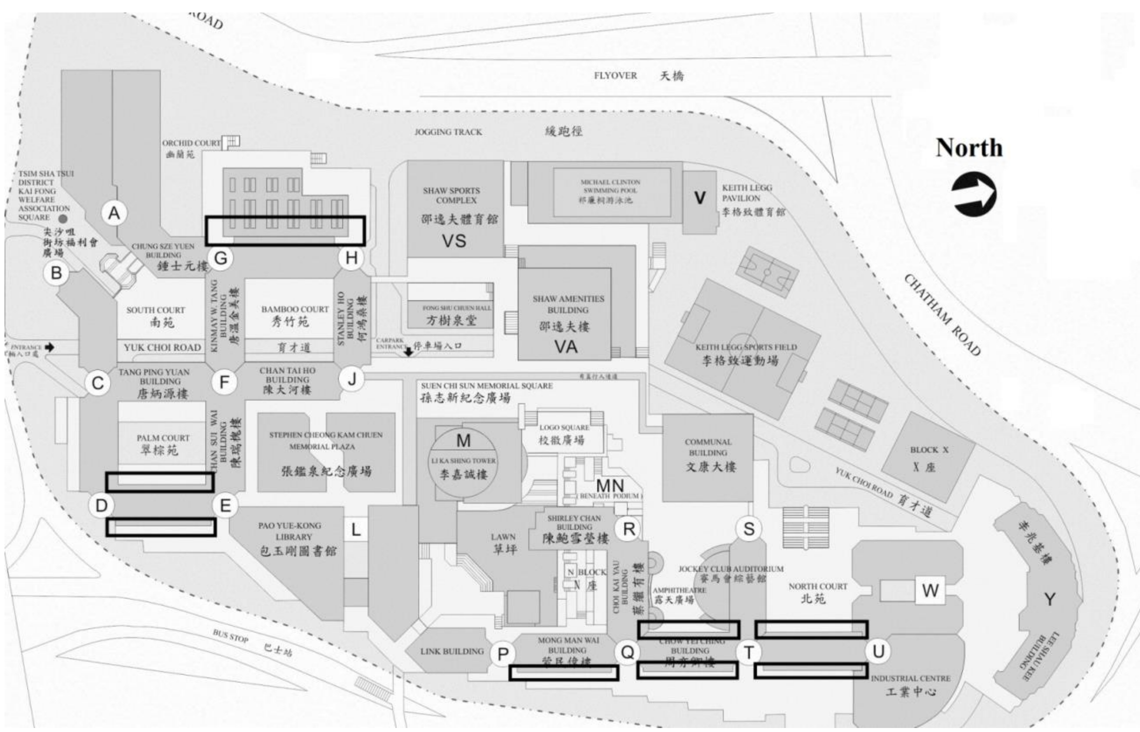


Figure 5. 1 Campus map of the university (those marked-up blocks are identified for external shading installation)

The reasons for choosing overhang shading are as follows: Hong Kong is located within a humid subtropical climate zone, with abundant rainfall as well as a considerable number of thunderstorms and typhoons. Thus during design of external building structures, security factors under extreme weather condition should be taken into serious consideration. Of all the external shading devices considered, overhang is the most reliable in term of structure. Besides, after its construction, overhang shading system could stay effective without routine maintenance. As long as its structure stays stable, the system could be cleaned by natural rain and wind blow. Also, although it could reduce most solar heat gain, vertical type sunshades would block most of the view from window glazing, which is considered to be a very important feature for high-rise buildings. Moreover, there are buildings already with overhang installed on their facades. In order to keep appearance of campus buildings identical, overhang is chose in the end.

Figure 5.2 shows details of the shading installation proposed by a design company. The installation applies GMS and aluminum as supporting structure materials and the supporting structure is connected to the building facades with expansion screws. Fiber glass grating platform with a thickness of 38mm is utilized as shading platforms, and is embed into the GMS layer with screws. Aluminum cladding is used as protective layer, which covers the whole equipment up. The appearance of the building after construction is shown in Figure 5.3. The amounts of different building materials required in construction are listed in Table 5.1. It should be noticed that materials needed for welding, sealing and jointing are not listed separately, but the energy and CO_2 emission associated with these products will be considered in on-site construction activity.

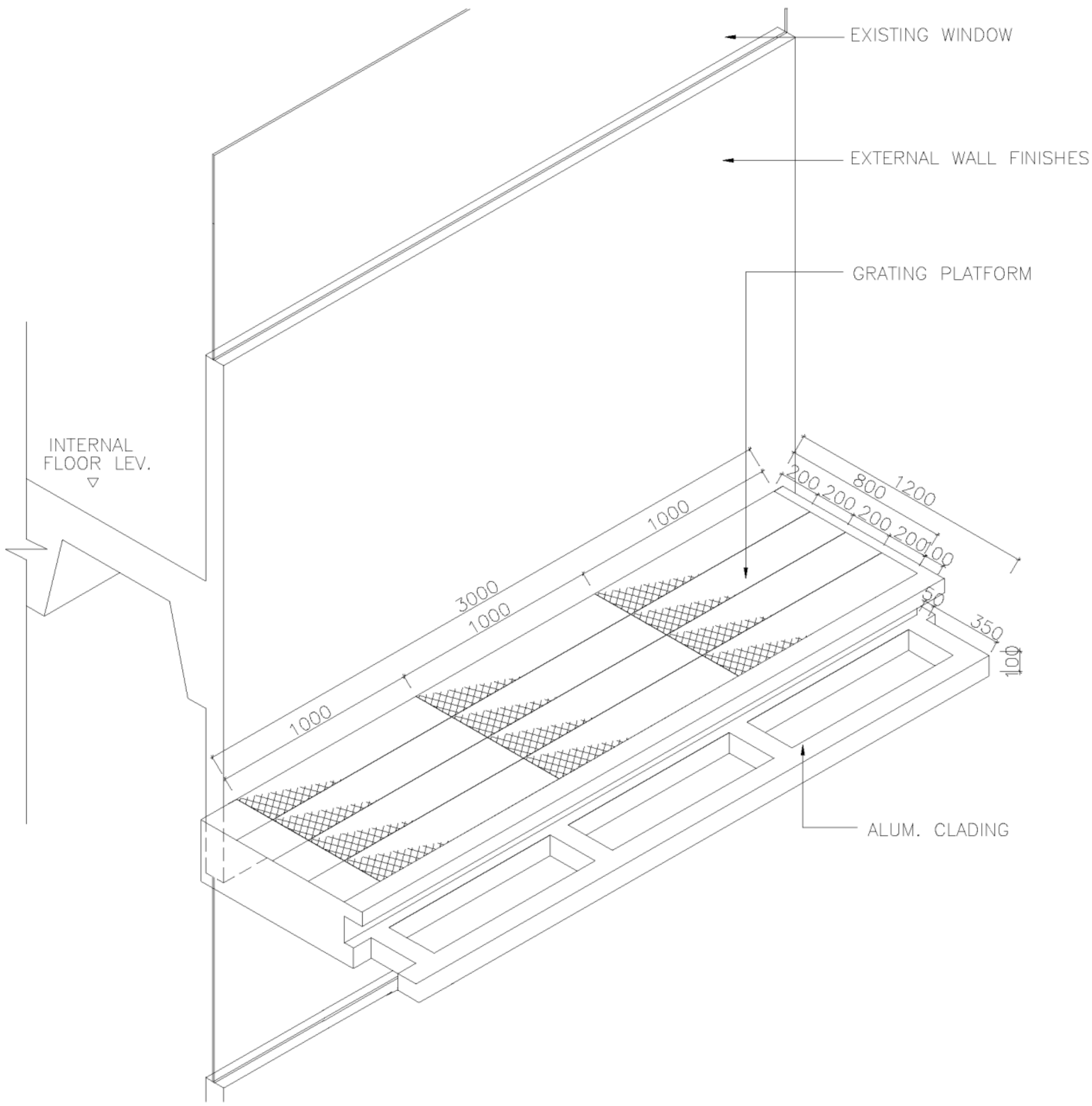


Figure 5. 2 Schematic of the shading system design

Figure 5. 3 Rendering of the shading system

Table 5. 1 List of materials required in construction

Item	Amount	Item	Amount
East Wings			
For Wing DE		*For Wing PQ*	
Fiber glass grating platform	$224m^2$	Fiber glass grating platform	$269m^2$
GMS structure	43,960 kg	GMS structure	52,752 kg
Aluminum structure	1,400 kg	Aluminum structure	1,680 kg
Aluminum cladding	$616m^2$	Aluminum cladding	$739m^2$

For Wing QT		*For Wing TU*	
Fiber glass grating platform	$269m^2$	Fiber glass grating platform	$237m^2$
GMS structure	52,752 kg	GMS structure	46,472 kg
Aluminum structure	1,680 kg	Aluminum structure	1,480 kg
Aluminum cladding	$739m^2$	Aluminum cladding	$651m^2$
West Wings			
For Wing DE		*For Wing GH*	
Fiber glass grating platform	$144m^2$	Fiber glass grating platform	$269m^2$
GMS structure	28,260 kg	GMS structure	52,752 kg
Aluminum structure	900 kg	Aluminum structure	1,680 kg
Aluminum cladding	$396m^2$	Aluminum cladding	$739m^2$
For Wing QT		*For Wing TU*	
Fiber glass grating platform	$173m^2$	Fiber glass grating platform	$173m^2$
GMS structure	33,912 kg	GMS structure	33,912 kg
Aluminum structure	1,080 kg	Aluminum structure	1,080 kg
Aluminum cladding	$475m^2$	Aluminum cladding	$475m^2$

After the design is finalized, the Campus Development Office issues an invitation for bids to several local construction companies for this project, and received a lowest bid price which charged 29,784,000 HKD for the project.

5.3.2 Energy Performance of the Overhang System

With the reference of annual solar irradiance data from the Hong Kong Observatory, plus the glazing parameters of university buildings, a special program was developed to estimate energy performance of the involved window glazing.

The window glazing utilized in the university campus is 6mm thick single clear layer type. The east facing window area is 970.25m^2, while the west facing window area is 867.8m^2. All the involved windows are located in corridors, and there are no interior shading systems utilized.

Table 5. 2 Glazing system specification

Incidence Angle	0	10	20	30	40	Diffuse
SHGC	0.859	0.859	0.857	0.854	0.845	
Incidence Angle	50	60	70	80	90	0.781
SHGC	0.825	0.779	0.667	0.418	0	

In an earlier study, four offices with same size and same window area, respectively facing east, west, south and north were selected to test their space cooling load within a typical summer day. During the test, no internal load was presented, and temperature set-points were the same for all involved rooms as well as the adjacent rooms, thus the cooling load handled by air-conditioning system was all caused by radiation and convection heat transfer on the exterior walls (Wong & Niu, 2008). By comparing the actual test data with the calculation result in this paper, we discovered that simulation result and measured data fit quite well, which indicates that the program's accuracy is reasonable, though the maximum cooling load appears a little earlier than previous result. The reason is because in this paper only radiation heat gain through window glazing is considered, while the onsite monitoring included both radiation and convection heat gain through the exterior wall area.

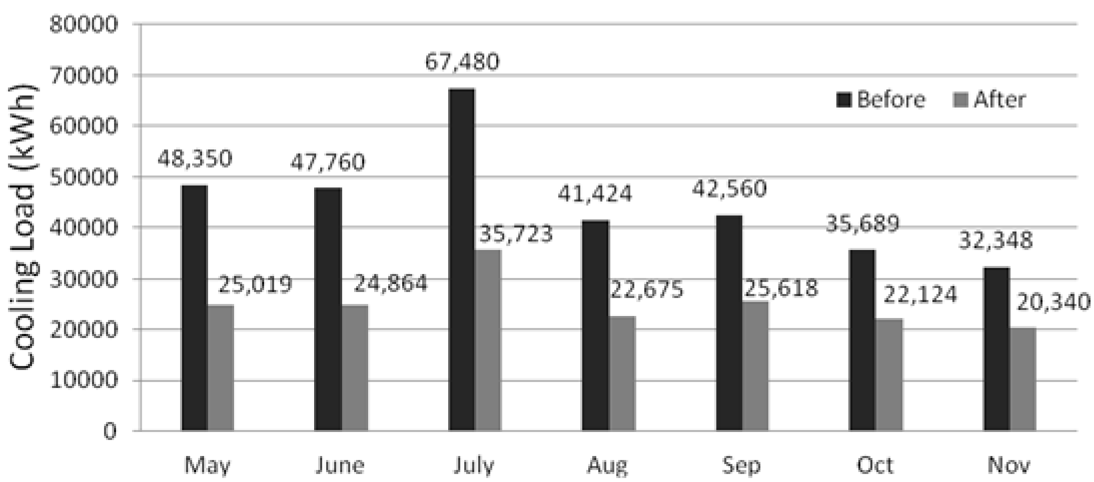


Figure 5. 4 Monthly reduction of cooling load caused by shading system

Figure 5.4 gives the monthly cooling load caused by involved window glazing before and after installation of the overhang shading system. After application of the solar shading system, the annual space cooling load caused by involved window glazing is reduced by about 139,250 kWh, which shows a reduction of 44.1%.

5.3.3 Life Cycle Analysis of the Overhang System

During the project, the amount of aluminum structure needed is 10.98t, and the amount of aluminum cladding needed is 4830m^2. Consider the aluminum cladding is 3mm thick and the density of aluminum is 2.7t/m^3, the total amount of aluminum needed in the project is 50.1t. According to Tan and Khoo (2005), the CO_2 emission coefficient for aluminum is 18.3t-CO_2/t, and the embodied energy coefficient for aluminum is 57.33 GJ/t. The amount of GMS structure needed is 344.772t. Bolin and Smith (2010) argued that the CO_2 emission coefficient for GMS structure is 3.133t-CO_2/t, while the embodied energy coefficient for GMS structure is 32 GJ/t. The amount of fiber glass grating platform needed is 2060m^2. Considering the density of 38 mm thick fiber glass grating platform to be 23.8 kg/m^2, the required mass of fiber glass materials is 49.03t. Nicolier et al. (2001) claimed that the CO_2 emission coefficient for fiber glass grating is 4.873t-CO_2/t. Song et al. (2009) claimed that the embodied energy coefficient for fiber glass grating platform is 169.69 GJ/t. The coefficients and calculation result of the materials are collected below in Table 5.3.

In order to estimate the environmental effect caused by transportation, the location of origins and manufacturers should be determined. In this case, the following assumptions are made so that environmental impacts of the project could be minimized: required building materials are all acquired from the nearest origin in Mainland China, the manufacturers are located at the same place with mining and refining plant, the construction company is located in Hong Kong. Detailed information of transportation is collected in Table 5.4. The total environmental impact caused by manufacture and transportation of materials are collected in Table 5.5.

It is very hard to get a systematical method to precisely estimate the energy consumption and CO_2 emission of a specific site construction. Existing literatures are mainly statistics of isolated cases. In this case, the structure of the shading system was designed under severe weather conditions, thus had the strength comparable to ordinary building floors. In order to estimate energy consumption and CO_2 emission during construction, previous data on projects with similar structure style is applied. The CO_2 emission coefficient is a standard unit for greenhouse gas emission calculation in Life Cycle Analysis. It stands for the amount of CO_2 emission caused during manufacturing of materials per unit weight or transportation of materials per unit weight through per unit distance.

Table 5. 3 Environmental impact of building materials manufacture

Item	Aluminum	GMS	Fiber glass
Mass (t)	50.1	344.77	49.03
CO_2 emission coefficient (t-CO_2/t)	18.3	3.133	4.873
CO_2 emission amount (t)	916.83	1080.16	238.92
Embodied energy coefficient (GJ/t)	57.33	32	169.69
Embodied energy (GJ)	2872.23	11032.64	8319.9

Table 5. 4 Environmental impact of building materials transportation

Item	Aluminum	GMS	Fiber glass
Mass (t)	50.1	344.77	49.03
Origin	Zunyi, Guizhou	Shenzhen, Guangdong	Shenzhen, Guangdong
Distance(km)	1800	50	50
CO_2 emission coefficient (g-CO_2/tkm)	70	70	70
CO_2 emission amount (t)	6.32	1.2	0.2
energy consumption coefficient (MJ/tkm)	1.8	1.8	1.8
Energy consumption (GJ)	162.32	31.1	4.4

Table 5. 5 Environmental impacts summary for material preparation

Item	Manufacture	Transportation	Total
CO_2 emission amount (t)	2235.91	7.72	2243.65
Energy consumption (GJ)	22224.77	197.82	22422.59

The shading system utilized GMS as structure material, thus could be compared with steel structured buildings. The materials required in the system were: 50.1t of aluminum, 344.77t of GMS and 49t of fiber glass grating platforms, and the constructed platform area is 2060m2, thus the density of the structure material was 215.5kg/m^2. According to Mithraratne and Vale (2004), energy required for on-site construction of buildings with similar structure was 470MJ/m^2. Buchanan and Honey (1994) claimed that the CO_2 emission due to on-site construction of buildings with similar structure was 39.5kg-CO_2/m^2. The environmental impacts caused by on-site construction are collected in Table 5.6.

Table 5. 6 Environmental impacts summary during on-site construction

Item	CO_2 emission	Energy consumption
area	2060m^2	2060m^2

Coefficient	39.5kg-CO_2/m^2	470MJ/m^2
Amount	81.37t	968.2GJ

From above calculation result it is clear that a 139,250 kWh annual cooling load reduction could be expected. Considering the COP of the air conditioning system to be 2.5, an annual saving of 55,700 kWh in electricity consumption could be expected. According to Lu et al. (2010), the CO_2 emission coefficient for electric-power generation in Hong Kong is 671g-CO_2 /kWh, thus the annual CO_2 emission reduced from the system application could be calculated to be 37.6t-CO_2. Considering the electricity generation efficiency to be 38%, the annual saving of primary energy could be calculated to be 527.68GJ.

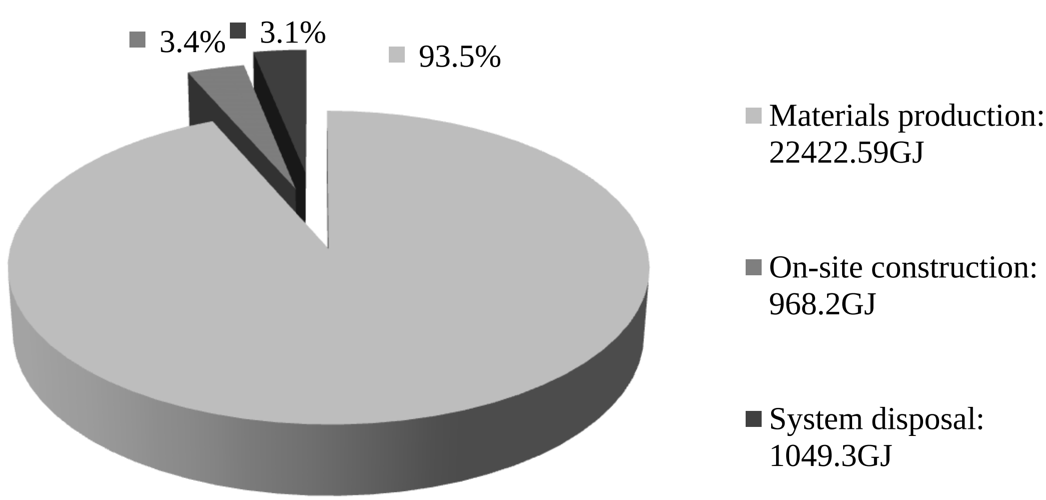
As mentioned before, the Campus Development Office intended to make no maintenance during the overhang shading system's life cycle, thus during system operation period, energy consumption and CO_2 emission from system maintenance stay zero.

According to Suzuki and Oka (1998), energy consumption coefficient for demolition work of the shading system should be 490MJ/m^2, and the CO_2 emission coefficient should be 36kg-CO_2/m^2. Considering the disposal plant to be located in local area, the transport distance of system disposal could be assumed to be 50km. Table 5.7 collects the environmental impact during the system disposal period.

Figure 5.5 gives a summary of the life cycle environmental impacts caused by installation of the shading system.

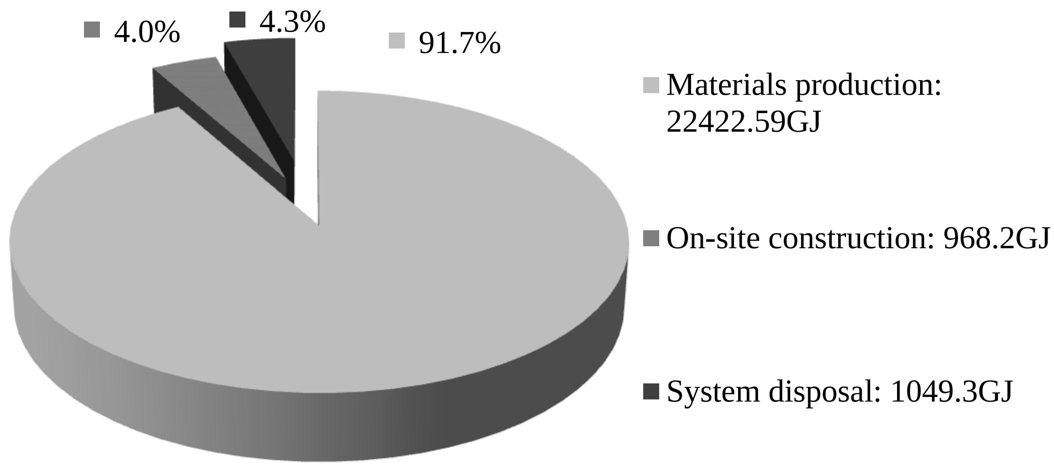
Table 5. 7 Environmental impacts during system disposal period

Item	CO_2 emission	Energy consumption
Area	$2060m^2$	$2060m^2$
Demolition coefficient	$36kg\text{-}CO_2/m^2$	$490MJ/m^2$
Demolition amount	$74.16t\text{-}CO_2$	1009.4GJ
Disposal distance	50km	50km
Disposal mass	443.87t	443.87t
Disposal coefficient	$70g\text{-}CO_2/tkm$	1.8MJ/tkm
Disposal amount	$1.55t\text{-}CO_2$	39.9GJ
Total amount	$75.71t\text{-}CO_2$	1049.3GJ



Total CO_2 emission: 2400.73t

A. CO_2 emission



Total energy consumption: 24440.1GJ

B. Energy consumption

Figure 5. 5 Life cycle environmental impacts summary

As has been mentioned above, the annual saving in electricity consumption should be 55,700kWh, with the electricity price to be 0.94HKD/kWh, the annual money saved could be expected to be about 52,400HKD.

As previously mentioned, the lowest bid price the Campus Development Office of the university received charged 29,784,000 HKD for the project. It should be noticed that practically, the bidder with the lowest charge is not the best choice in most cases. Due to cost cuts, the quality of their construction staff maybe not as good, their management and cooperation level may be quite low, the quality of materials they purchase may not be the best, thus the quality of their projects is usually not very good.

In this case, even if the Campus Development Office chose the lowest bidder for the project, the financial investment would still be nearly 30 million HKD. Compared with the annual savings of 52,400 HKD, it is quite impossible to expect the investment to be recovered within the life cycle of the project, not to mention if bidders with higher charges were selected.

The annual saving of primary energy from application of the shading system is 527.68GJ, while the life cycle energy consumption caused by the system is24440.09GJ, according to formula 5.1, the energy payback period of the shading system could be calculated to be about 46.3years.

The annual CO_2 emission reduced from application of the shading system is 37.6t-CO_2, while life cycle CO_2 emission caused by the system is 2400.73t, according to formula 5.2, the CO_2 emission payback period of the shading system could be calculated to be about 63.8 years. After careful consideration on the analysis result, the Campus Development Office of the university eventually gave up this retrofitting project.

5.3.4 Discussion of the Calculation Result

From the above calculation it is clear that the benefit from installation of exterior shading system is quite unsatisfactory. During life cycle, the shading system makes little contribution to energy conservation. When it comes to the reduction of CO_2 emission, the shading system even makes a negative effect considering the lifetime of an exterior shading system is normally 50 years. This situation should be largely attributed to geographical location and climate of Hong Kong.

As mentioned above, Hong Kong is located within a humid subtropical climate zone, with abundant rainfall as well as a considerable number of thunderstorms, tropical storms or typhoons. Thus during design of external building structures, structural engineers tend to make the structure as strong as possible, so that their projects could definitely stand firm during extreme weather situation. Such guideline inevitably leads to an extensive application of high-strength building materials, which in term causes large amount of energy investment as well as CO_2 emission. In this case, the area of involved window glazing is about 1838m^2, while over 440t building materials are utilized, which means an object weighing over 240kg is hang on the top of every window involved. It is also quite clear from Figure 5.6, impacts caused by materials preparation takes a dominant part in the total environmental impacts due to the project. Same conclusion could also be drawn from detailed breakdown of budget from the lowest bidder, which is presented in Figure 5.6.

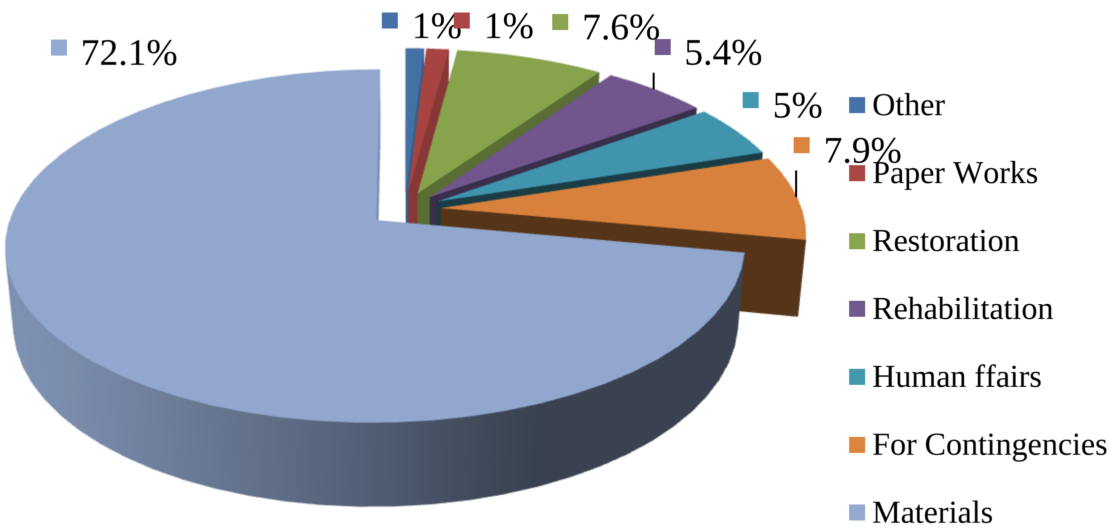
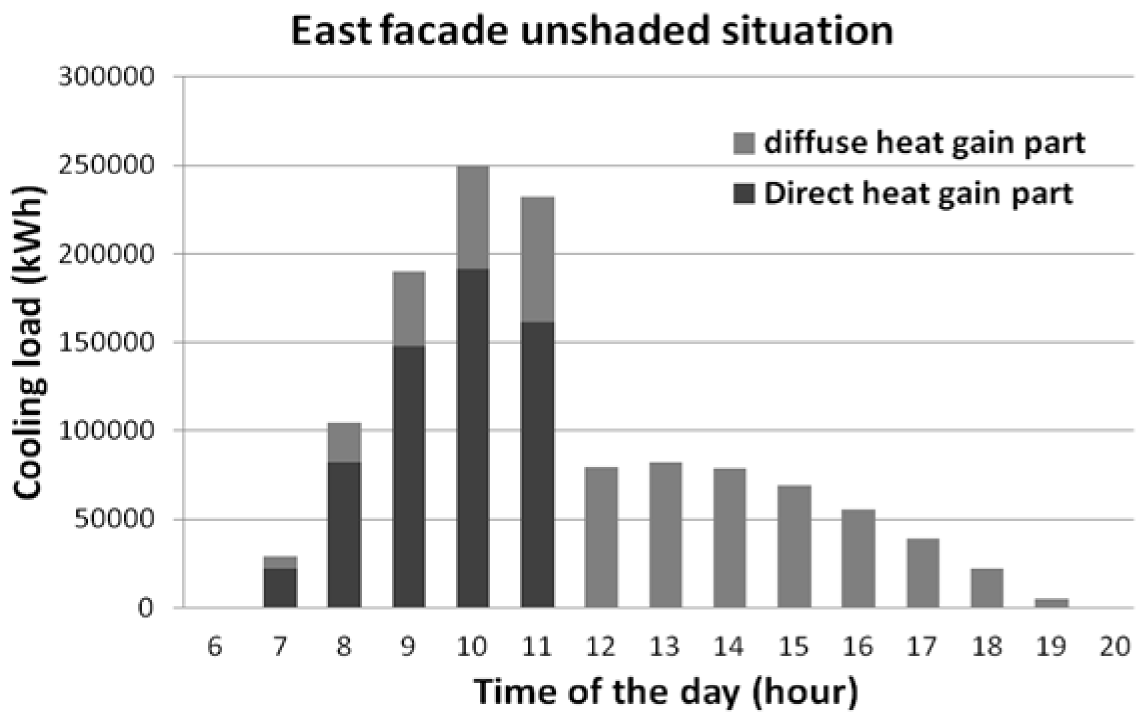


Figure 5. 6 Detailed breakdown of the bidder budget

Of the 29,784,000 HKD charged for the project, more than 72% would be spent on materials preparation. Considering the relatively high level of local labor cost, the cost of materials is still too high for a retrofitting project. Compared to the annual money saved of 53,400 HKD, high investment of this sort of projects surely cannot interest decision-makers.

It should be noted that above discussion is based on a building retrofitting case, when it comes to cases of new building constructions, result may be different. During building design period, external shading system could be designed as part of building frame, which may considerably reduce the investment. In addition, special design could be made on building style to avoid direct solar irradiance on window glazing, which may also contribute to reduction of radiation heat gain.

On the other hand, it is clear that shading system will make more contribution during periods when there occurs direct solar irradiance on window glazing. The latitude of Hong Kong is 22°15´, which means in most time of a year, Hong Kong has a higher solar elevation angle than inland area to its north. This feature determines that in low-latitude regions such as Hong Kong, large part of the solar direct irradiance projects on the roof area of buildings, and windows facing east and west could only receive solar direct irradiance for a relatively short period. Figure 5.7 shows the calculation result of performance of the shading system with and without solar direct irradiance in a typical summer day (July 22). It is clear that under direct solar irradiance, shading system could block out considerably more radiation heat gain. When there is no direct solar irradiance, the performance of shading system is significantly weakened. It also can be concluded that for windows facing both directions, there would be no solar direct irradiance in nearly half of the daytime, which significantly weakens the shading function of the system and thus lead to a low annual benefit in energy saving term.


East facade unshaded situation
diffuse heat gain part
Direct heat gain part
Cooling load (kWh)
300000
250000
200000
150000
100000
50000
0
6
7
8
9
10
11
12
13
14
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16
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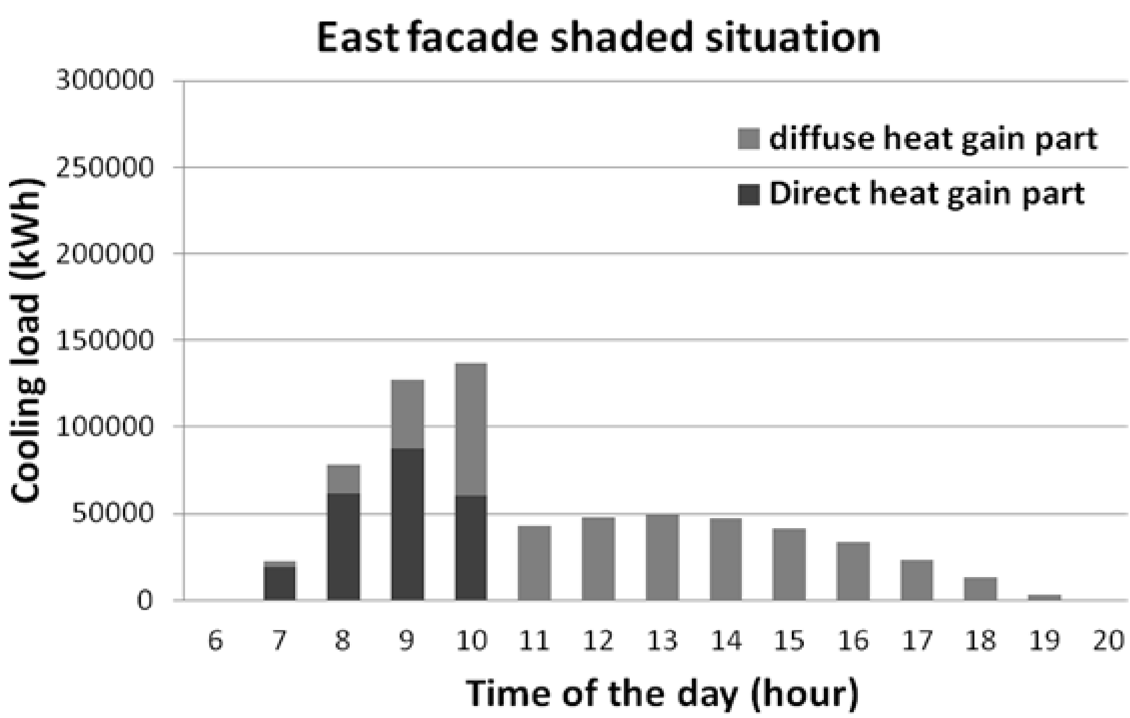
19
20
Time of the day (hour)


East facade shaded situation
diffuse heat gain part
Direct heat gain part
Cooling load (kWh)
300000
250000
200000
150000
100000
50000
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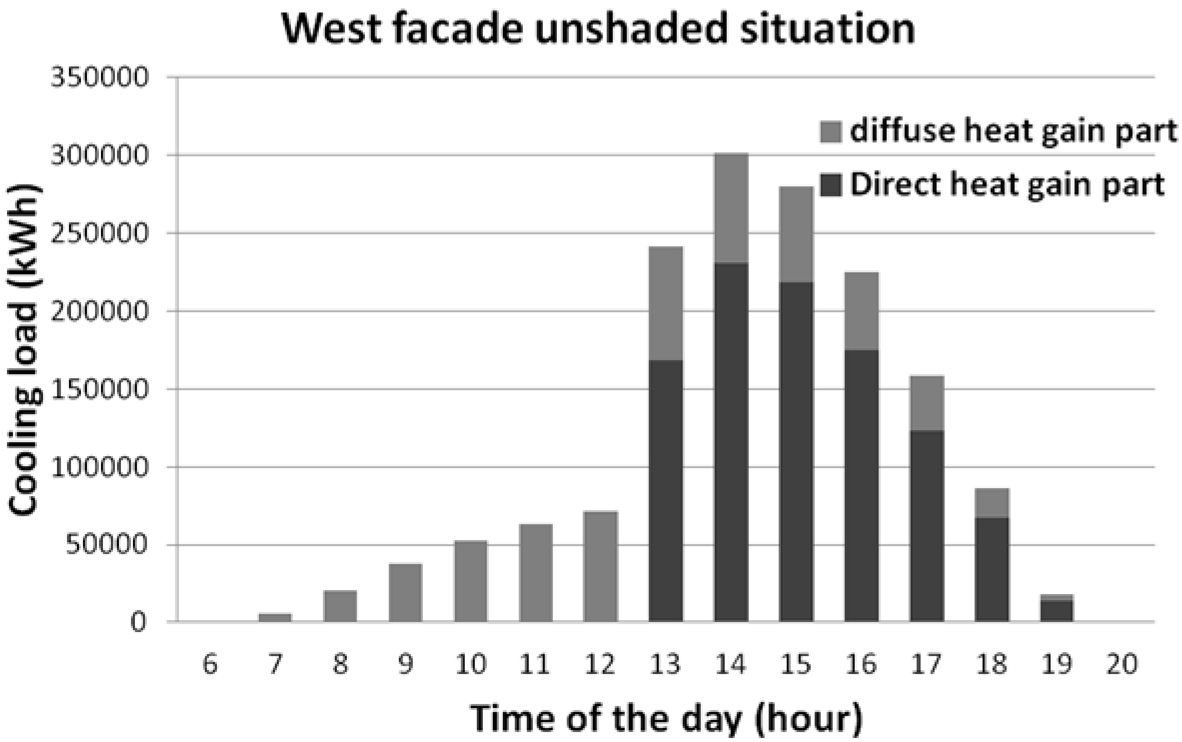
Time of the day (hour)



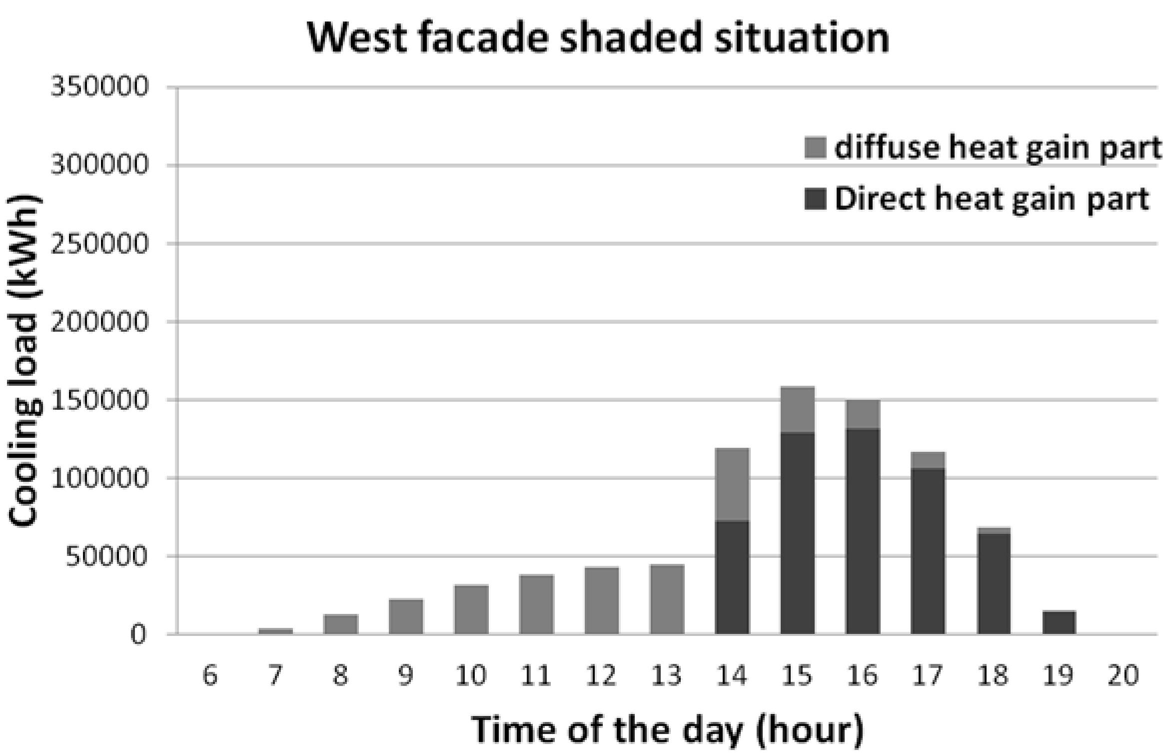


Figure 5. 7 Effect of the shading system with and without solar direct irradiance

5.4 Summary

In this chapter, a methodology for analyzing life cycle environmental impacts of external shading system is described in details, and a case study is also presented for reference. The case involves an external overhang shading system retrofitting project on several teaching buildings in a university campus of Hong Kong. The life cycle energy consumption and CO_2 emission caused by the overhang system are carefully collected; the annual environmental benefit is also calculated. Result shows that based on financial consideration, it takes unacceptable long to recover the economic investment on the overhang system, the application of shading system could only make a very limited contribution to energy conservation. When it comes to CO_2 emission reduction, the overhang system even makes a negative effect. The reasons causing this situation are mainly related to geographical and meteorological factors of Hong Kong's location.

In order to resist typhoons during summer in Hong Kong, designers tend to use large amount of strong building materials to reinforce their outdoor structures, which leads to a large amount of investment. Besides, the low latitude of Hong Kong significantly reduces the blocking effect of external overhang shading system, which causes the low annual benefit on energy conservation. Thus in area with similar climate, interior shading system and advanced energy-efficient glazing system are suggested.

External overhang retrofitting may not be applicable in low-latitude humid subtropical climate area such as Hong Kong, and people should sort for other solutions for reducing radiation heat gain. For instance, glass with better thermal performance or advanced structures could be utilized; external shading options with less investment and higher performance could be considered.

Life cycle analysis could be an important reference for energy –efficient retrofitting project under different climate situations. Launching LCA before an energy-efficient retrofitting project is quite necessary for avoiding being counterproductive.

Chapter 6

Daylighting Performance of Energy-Efficient Window Designs in Commercial Buildings

6.1 Introduction

The demand for energy is increasing faster with the development of civilization and society, while the amount of non-renewable primary energy is decreasing even faster. In order to ensure the continued development of human civilization, efforts should be made on both the search of new energy source and improvement of current energy efficiency such as reducing the consumption of energy. In other words, energy-saving is of great significance to the human-being.

Commercial building consume over one-third of the total primary energy requirement in developed countries, and the amount of this building is increasing at a rapid speed. Building energy management is one of the most direct and effective way to relieve the energy shortage. Electric lighting accounts for about 25% of total building energy use, which has a great potential for energy-saving.

Daylight is often considered as the best source of light for good colour rendering and closely matches human visual response. It does make an interior space look more lively and attractive. The daylight entering a building through window provides the dual function not only of admitting light into the indoor environment, but also in connecting the outside world to the inside of a building. People expect good natural lighting in their working places.

Daylighting is the practice of placing windows or other openings and reflective surfaces so that during the day natural light provides effective internal lighting. Particular attention is given to daylighting while designing a building when the aim is to maximize visual comfort or to reduce energy use. Energy savings can be achieved either from the reduced use of artificial (electric) lighting or from passive solar heating or cooling. Daylight can offset lighting energy use and the heat gains associated with the electric lighting system, but the admission of too much daylight can increase cooling load associated with solar heat gain, the benefits from daylight may be penalized by the corresponding increase in solar heat gain. Moreover, the small angle of incidence can made direct sunlight excessive. To avoid the problems of glare, excessive brightness and thermal discomfort, occupants may block the windows with internal shading devices, resulting in poor daylighting performance and very small electric lighting energy savings.

Daylighting could be considered as a most traditional and popular architecture design all over the world. Existing studies mainly focus on the visual comfort features in daylighting design. Few researchers combine thermal and visual performance together. In this chapter, a popular daylighting energy simulation tool Daysim is applied to study the daylighting energy saving potential of several energy-efficient designs on commercial building envelope in cooling-dominant climates. Different factors that may influence the daylighting performance are investigated and discussed. A comprehensive evaluation which combines both visual and thermal performance of the design measures is also conducted.

It should be noticed that due to the commercial property of shopping mall, though there exists daylighting design in shopping mall type commercial buildings, daylighting control strategies are seldom applied. The purpose of daylighting design in shopping mall is more inclined to visual comfort rather than energy efficiency. Also, due to their commercial property, few hotel buildings apply large amount of shading devices. According to above consideration, in the daylighting simulation study, only hotel and office building are considered. In the simulation of advanced glazing material application, both hotel and office building are considered. In the simulation of shading device application, only office building is considered.

6.2 Detailed Settings for Daylighting Simulation

The daylighting simulation is based on the same building model that used in thermal simulation above. Two different building types are considered in daylighting simulation: hotel and office. For commercial reasons, daylighting designs in shopping mall are mostly passive. Seldom shopping malls have artificial linked daylighting strategy. Thus in the study of building envelope daylighting performance, only hotel and office are taken into discussion.

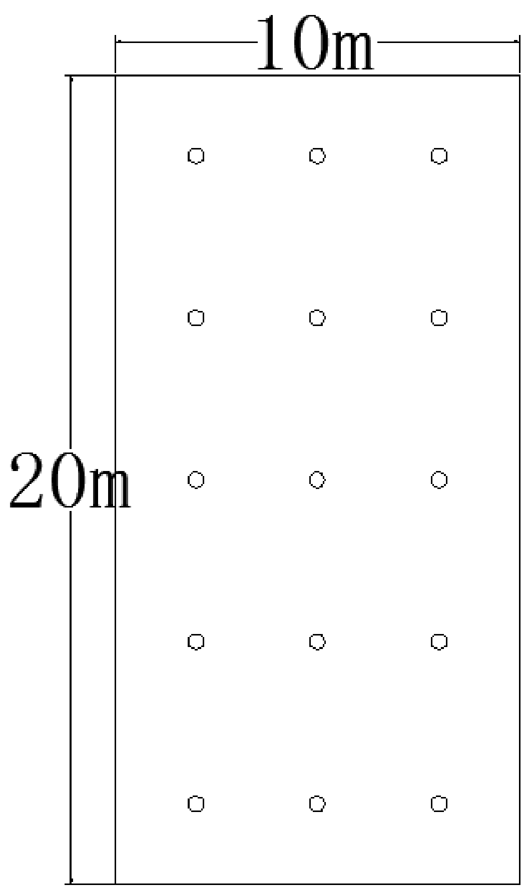
In order to assessing the visual environment inside a room, illumination level is not the only parameter that matters. Illumination distribution is also an important evaluation. If the illumination level in a small area has significantly deviations (no matter too low or too high) with surrounding, visual environment will be uncomfortable. In this situation, occupants will prefer to open the artificial lighting to maintain a satisfactory visual environment. According to this consideration, a considerable number of illumination reference points are distributed within a room.

Figure 6.1 presents the distribution of illumination reference points and artificial lighting equipment within a single room. As mentioned above in Table 4.3, the occupant densities in office and hotel building are $13m^2$/person and $25m^2$/person, respectively. The lighting energy density in office and hotel building are $15W/m^2$ and $17W/m^2$, respectively. The indoor illumination level set point is 500 lux. The lighting control system is set to be: "Manual on/off switch near the door". The height of illumination measuring points is 0.8 m, which is a typical height of working desk. The maximum allowable Discomfort Glare Index is 22 (Hong Kong Government, 2007). When visual discomfort occurs at a reference point, the artificial lighting equipment responsible will be turned on immediately.

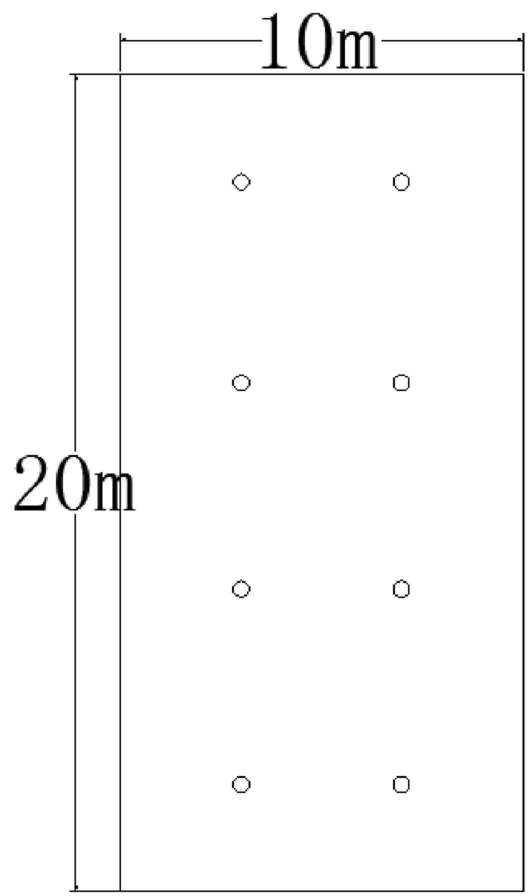
During the daylighting simulation, two different occupant behavior models were applied. For the first occupant behavior model, occupants were considered to have no daylighting awareness. They will turn on the light above their seats once they arrive at the office, and switch it off while they leave. Under this condition, there was no dimming control of the artificial lighting. The artificial lighting system was set to be strictly operated according to the schedules in Figure 2.The simulation based on the occupant behavior model is serving as the Base Case. While in the Contrast Case, the occupants were supposed to consider daylighting as priority. While they arrive at the office, the artificial lighting system is off by default, and daylighting is first considered. Only when the illumination level is lower than 500 lux or glare appears, artificial lighting system will be turned on. For office building, the occupancy hour is set as 6:30 to 23:00, the lunch break is not considered. For hotel building, the occupancy hour is set as 0:00 to 24:00. After the simulation of building envelope thermal performance, energy saved from heat gain reduction is received. After the simulation of building envelope daylighting performance, energy saved from artificial lighting system is received. Combining these data together, a comprehensive evaluation could be obtained.

In order to study the impact of orientation on the daylighting performance, separate rooms are divided into four groups. Figure 6.2 shows the location of four groups. When daylighting performance of east-facing façade is discussed, rooms in Group A will be operating with daylighting strategy, while other rooms do not apply any daylighting strategy. When daylighting performance of south-facing façade is discussed, rooms in

Group B will be operating with daylighting strategy, while other rooms do not apply any daylighting strategy. When daylighting performance of west-facing façade is discussed, rooms in Group C will be operating with daylighting strategy, while other rooms do not apply any daylighting strategy. When daylighting performance of north-facing façade is discussed, rooms in Group D will be operating with daylighting strategy, while other rooms do not apply any daylighting strategy.

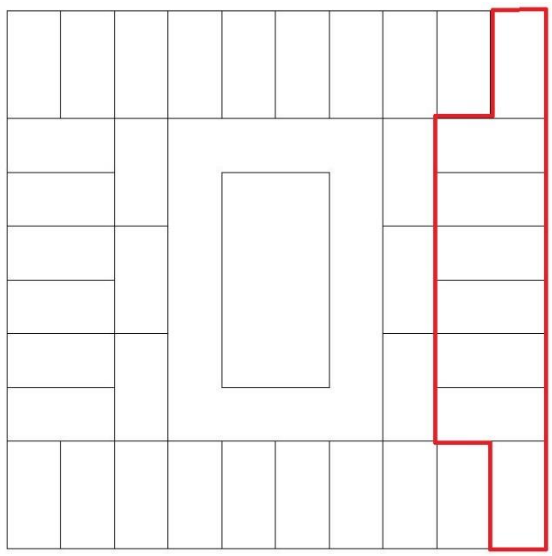


A. Office

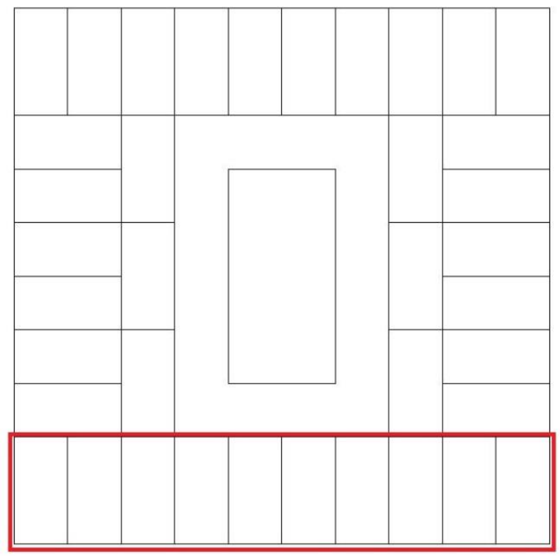


B. Hotel

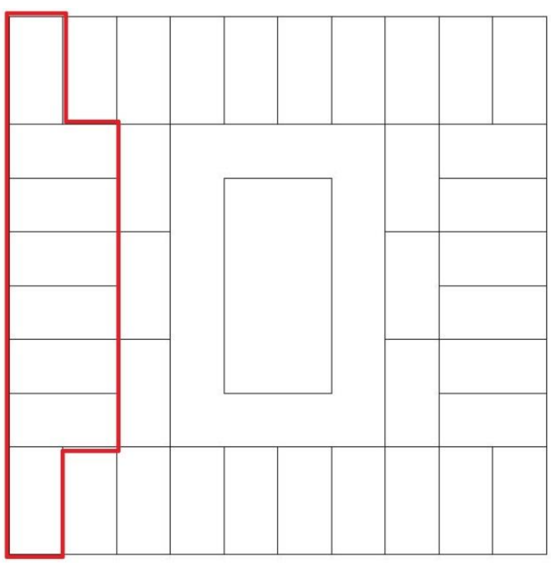
Figure 6. 1Distribution of illumination reference points and artificial lighting equipment



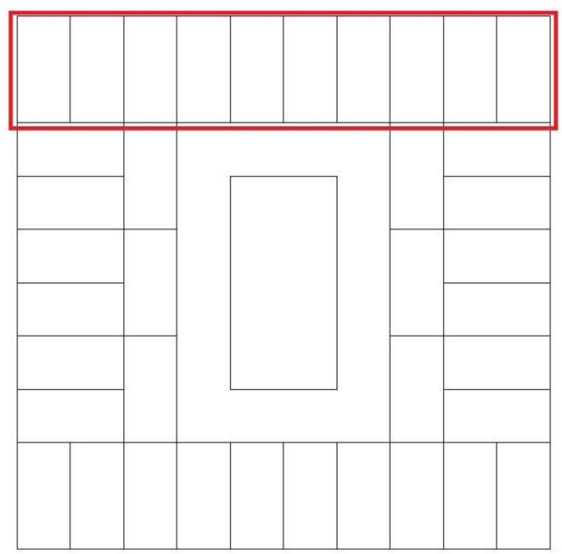
1. Group A



2. Group B



3. Group C



4. Group D

Figure 6. 2 Location of four groups during daylighting simulation

6.3 Simulation Results and Discussion

Before discussion, it should be noticed that in this simulation study, the model building is a simple square building with a large interior zone. The shape coefficient is quite small. Shape coefficient is the ratio of the area of building's external surface to the building's volume. The shape coefficient stands for the impact of external environment to the building's indoor environment. A small shape coefficient stands for a small impact of external environment to the building indoor environment (Long. 2005). Under this condition, the lighting energy saving from daylighting is relatively small. In smaller buildings or complex-shaded buildings, daylighting performance may be better.

6.3.1 Performance of Double-Layer Glazing

Table 6.1 gives the annual artificial lighting electricity reduction from application of daylighting strategy. The proportion of the annual reduction in total lighting electricity consumption is also presented. The double-layer glazing applied here is two layers of 6mm clear glazing with a 6mm air layer in between. In order to discuss the visual performance on different orientations, daylighting strategy is applied in different groups of small rooms separately according to Figure 6.1.in base case, no daylighting strategy is applied within the whole building. In different daylighting cases, the corresponding group of rooms is applied with daylighting strategy mentioned above.

Table 6. 1 Annual lighting energy saving from daylighting with the application of double-layer glazing

1. Singapore

Orientation	South	East	North	West
Office Building in Singapore				
Annual Reduction(kWh)	127834.22	138658.84	127405.91	138434.84
Proportion	1.64%	1.78%	1.63%	1.77%
Hotel Building in Singapore				
Annual Reduction(kWh)	49641.1	55613.6	49587.54	55451.9
Proportion	0.69%	0.78%	0.69%	0.77%

2. Hong Kong

Orientation	South	East	North	West
Office Building in Hong Kong				
Annual Reduction(kWh)	106814.3	121553.5	105599.8	122284.8
Proportion	1.37%	1.56%	1.35%	1.57%
Hotel Building in Hong Kong				
Annual Reduction(kWh)	42880.5	50782	42439	49515
Proportion	0.60%	0.71%	0.59%	0.69%

3. Miami

Orientation	South	East	North	West
Office Building in Miami				
Annual Reduction(kWh)	136980.59	142000.47	136524.28	143883.69
Proportion	1.76%	1.82%	1.75%	1.84%
Hotel Building in Miami				
Annual Reduction(kWh)	58740.5	61953.5	58626	62213
Proportion	0.82%	0.86%	0.82%	0.87%

4. Houston

Orientation	South	East	North	West

Office Building in Houston				
Annual Reduction(kWh)	136775.41	141377.25	135908.50	142659.34
Proportion	1.75%	1.81%	1.74%	1.83%
Hotel Building in Houston				
Annual Reduction(kWh)	58028.5	61556.5	57704.5	61400
Proportion	0.81%	0.86%	0.80%	0.86%

Performance of daylighting strategy on east and west orientations is better than that on south orientation, but the difference is decreasing with the latitude rises. Daylighting performance on north orientation is the worst, but as the latitude rises, the difference becomes less significant.

It is also clear that daylighting strategy applied in hotel building receives a much smaller effect than that in office building. The reason lies in the difference of occupant's schedule. In hotel though the lobby is occupied throughout the day, while most guest rooms are occupied only during the night when daylighting is not available. While in office building, the majority of activities take place during the day time.

6.3.2 Performance of Low-E Glazing

Table 6.2 gives the comparison of annual artificial lighting electricity reduction from application of daylighting strategy between application of double-layer glazing and low-e glazing. The low-e glazing material selected here is the low-e glazing applied in Case 4 of Chapter 4, with a solar transmittance at normal incidence of 0.4.

Table 6. 2Difference between annual lighting energy saving from daylighting with the application of double-layer glazing and low-e glazing (kWh)

1. Singapore

Orientation	South	East	North	West
Office Building in Singapore				
Double-layer glazing	127834.22	138658.84	127405.91	138434.84
Low-e glazing	127590.09	138553.63	127113.66	138290.69
Hotel Building in Singapore				
Double-layer glazing	49641.1	55613.6	49587.54	55451.9
Low-e glazing	49531. 0	55551. 5	49461. 0	55347. 5

2. Hong Kong

Orientation	South	East	North	West
Office Building in Hong Kong				
Double-layer glazing	106814.3	121553.5	105599.8	122284.8
Low-e glazing	106580.91	121325.09	105310.19	122012.84
Hotel Building in Hong Kong				
Double-layer glazing	42880.5	50782	42439	49515
Low-e glazing	42770.5	50675.5	42314	49380

3. Miami

Orientation	South	East	North	West
Office Building in Miami				
Double-layer glazing	136980.59	142000.47	136524.28	143883.69
Low-e glazing	136873.63	141881.25	136402.88	143797.06
Hotel Building in Miami				
Double-layer glazing	58740.5	61953.5	58626	62213
Low-e glazing	58669.00	61895.00	58545.50	62158.50

4. Houston

Orientation	South	East	North	West
Office Building in Houston				
Double-layer glazing	136775.41	141377.25	135908.50	142659.34
Low-e glazing	136670.19	141248.84	135781.41	142550.41
Hotel Building in Houston				
Double-layer glazing	58028.5	61556.5	57704.5	61400

Low-e glazing	57967.00	61474.00	57617.00	61323.00

Compared to double-layer glazing, daylighting performance of low-e glazing stays almost the same. Considering low-e glazing has a much better thermal performance than double-layer glazing, low-e glazing is a better choice for building energy management than double-layer glazing in cooling-dominant area.

6.3.3 Performance of Interior Blind

Table 6.3 presents the actual data and proportion of the annual artificial lighting electricity reduction from application of daylighting strategy while window area is equipped with interior blind. The reflectivity of the blind is 0.8. The tilt angle for the louvers varies from 90 °to 30 °. It should be noticed that during the simulation, only office building is considered.

Table 6. 3 Annual lighting energy saving from daylighting with the application of interior blind

1. Singapore

Tilt Angle	Orientation	South	East	North	West
90 °	Reduction(kWh)	68655.13	102694.81	64832.91	101550.09
	Proportion	0.88%	1.32%	0.83%	1.30%
60 °	Reduction(kWh)	39615.84	61396.13	40327.66	57889.78
	Proportion	0.51%	0.79%	0.52%	0.74%
30 °	Reduction(kWh)	0.00	14101.06	0.00	10896.59
	Proportion	0.00%	0.18%	0.00%	0.14%

2. Hong Kong

Tilt Angle	Orientation	South	East	North	West
90 °	**Reduction(kWh)**	60094.34	73331.78	52884.78	74564.44
	Proportion	0.77%	0.94%	0.68%	0.96%
60 °	**Reduction(kWh)**	28485.84	44829.97	25892.56	46795.66
	Proportion	0.36%	0.57%	0.33%	0.60%
30 °	**Reduction(kWh)**	0.00	8268.09	0.00	9559.38
	Proportion	0.00%	0.11%	0.00%	0.12%

3. Miami

Tilt Angle	Orientation	South	East	North	West
90 °	**Reduction(kWh)**	121544.94	125316.63	120855.44	127075.16
	Proportion	1.56%	1.61%	1.55%	1.63%
60 °	**Reduction(kWh)**	108892.88	115205.13	107232.56	116820.16
	Proportion	1.40%	1.48%	1.37%	1.50%
30 °	**Reduction(kWh)**	46842.03	64473.06	45825.72	61963.13
	Proportion	0.60%	0.83%	0.59%	0.79%

4. Houston

Tilt Angle	Orientation	South	East	North	West
90 °	**Reduction(kWh)**	117649.66	122167.28	116671.84	124333.13
	Proportion	1.51%	1.57%	1.49%	1.59%
60 °	**Reduction(kWh)**	102757.38	110370.75	100101.75	112118.13
	Proportion	1.32%	1.41%	1.28%	1.44%
30 °	**Reduction(kWh)**	42712.69	57797.91	41639.94	58478.44
	Proportion	0.55%	0.74%	0.53%	0.75%

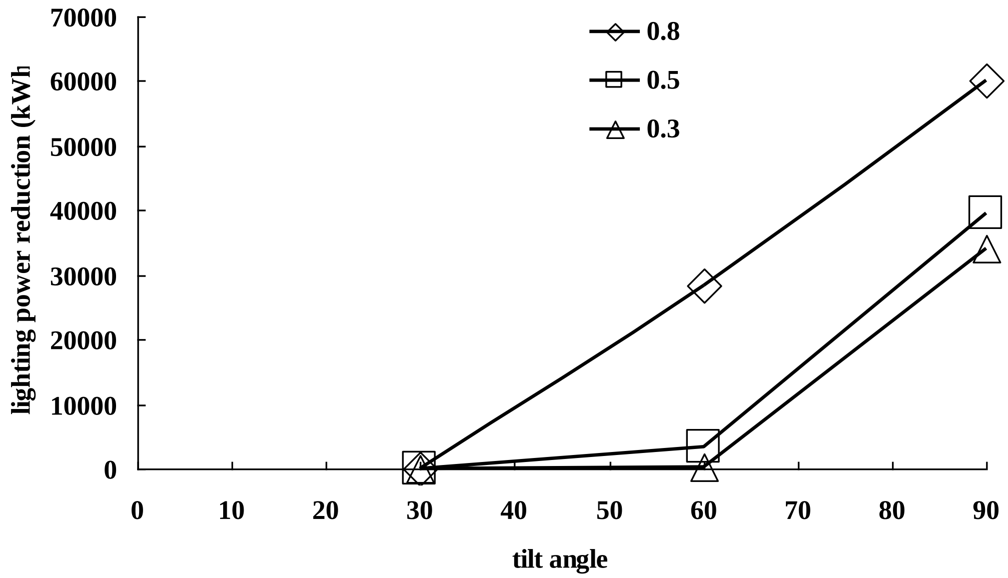
From above data several interesting conclusion could be achieved. In all cases, daylighting performance on east and west orientations is always better than that on south and north orientation. In low latitude area like Singapore, the difference is much larger. In double-layer glazing cases, the difference between daylighting performance of east, west orientations and south, north orientations is within 10%. However in interior blind shading cases, the difference is nearly 50% in Singapore and 25% in Hong Kong. Compared with double-layer glazing and low-e glazing cases, daylighting performance of interior blind in Singapore and Hong Kong is worse. While in Miami and Houston, the difference between daylighting performances of shading device and energy-efficient glazing is much smaller. In cooling-dominant area with relatively low latitude, application of interior blind will significantly affect the daylighting performance, while in area with high latitude the influence is not that much.

Performance of daylighting strategy on east and west orientations is better than that on south orientation, but the difference decreases with the latitude rises. Daylighting performance on north orientation is the worst, but as the latitude rises, the gap becomes less significant.

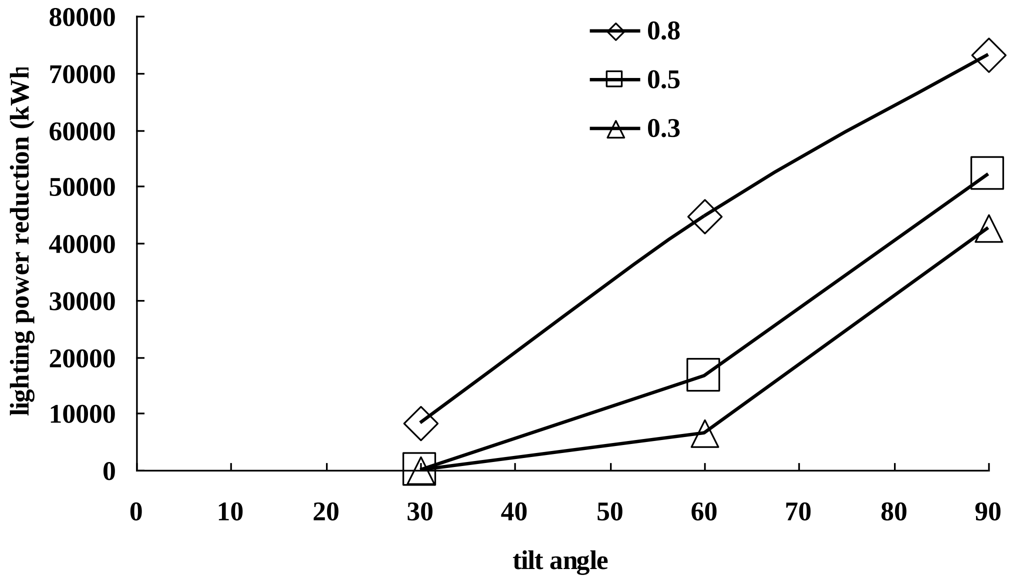
The tilt angle is an important factor that affects the daylighting performance of the interior blind. As shown in Table 6.3, in Singapore and Hong Kong, the daylighting performance drops very rapidly with the tilt angle. While the tilt angle decreases to 30°, Daylighting profits on south and north orientations completely disappear. Daylighting profits on east and west orientation also drop to a very low level. In Miami and Houston, though there is a drop on daylighting performance when the tilt angle gets smaller, daylighting effects on all orientations are still retained.

As mentioned in Chapter 4, occupant’s behavior can largely affect the performance of interior blind. Occupants do not adjust the blind very often (Zhang & Barrett, 2012; Wymelenberg, 2012). They tend to set the blinds in certain positions based on long-term perceptions of sun light and sun heat, and then just leave them there. In cooling-dominant climates with low latitude, the daylighting performance of interior blind is affected by occupant’s behavior much more significantly. While in area with relatively high latitude, impact of occupant's behavior on interior blind's daylighting performance is much smaller.

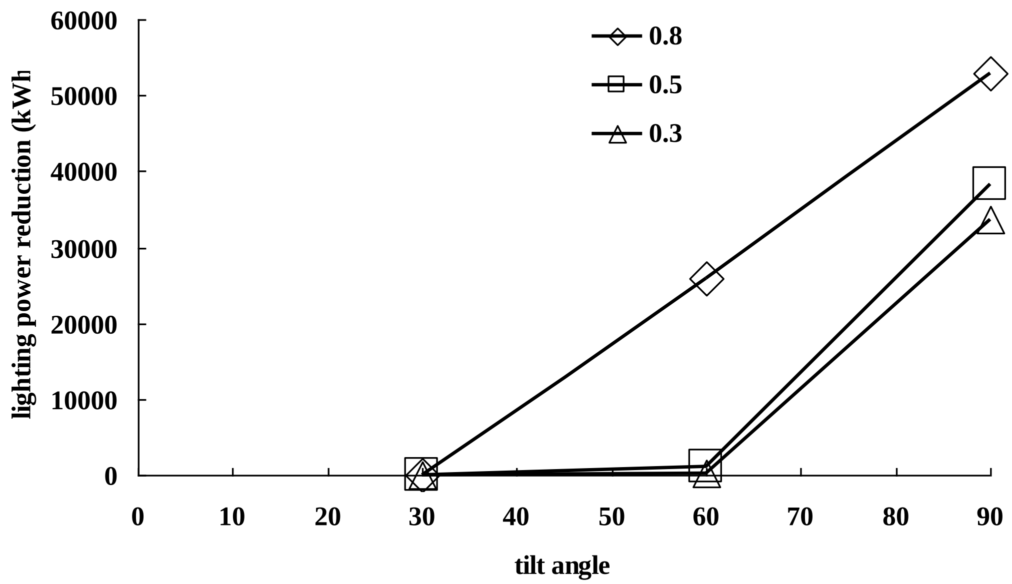
Louvers' reflectivity is an important parameter that affects the blind's performance. Take Hong Kong as an example, Figure 6.3 presents the impact of reflectivity on the daylighting performance of interior blind.



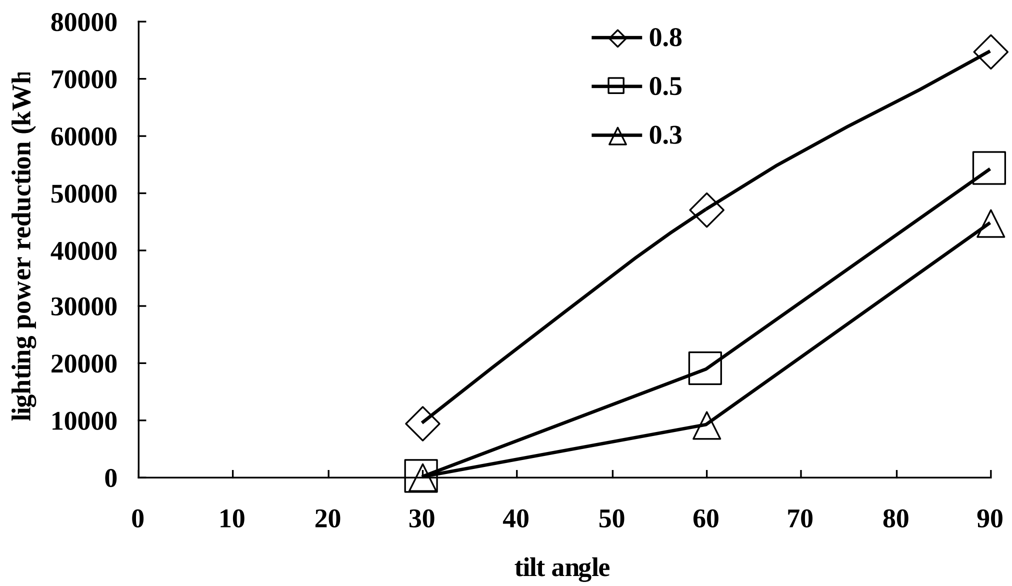
A. South orientation



B. East orientation



C. North orientation



D. West orientation

Figure 6. 3 Impact of reflectivity on the daylighting performance of interior blind in Hong Kong

From Figure 6.3 it is clear that as louver's reflectivity decreases, blind's daylighting performance also decreases. Also, as louver's reflectivity decreases, the impact of tilt angle on blind's daylighting performance becomes serious. Blind with high reflectivity has a better daylighting performance compared to others with lower reflectivity. The affection of occupant's behavior on daylighting performance of blind with high reflectivity is also weaker.

6.3.4 Performance of Overhang

Table 6.4 presents the actual data and proportion of the annual artificial lighting electricity reduction from application of daylighting strategy while window area is equipped with overhang. The depth of the overhang varies from 0.6m to 1m. It should be noticed that during the simulation, only office building is considered.

Table 6. 4Annual lighting energy saving from daylighting with the application of overhang

1. Singapore

Depth	Orientation	South	East	North	West
0.6m	**Reduction(kWh)**	121372.78	136502.19	121306.06	136295.69
	Proportion	1.56%	1.75%	1.55%	1.75%
0.8m	**Reduction(kWh)**	120297.63	136155.47	120363.25	135911.13
	Proportion	1.54%	1.74%	1.54%	1.74%
1m	**Reduction(kWh)**	118435.84	118896.53	118751.06	117841.06
	Proportion	1.52%	1.52%	1.52%	1.51%

2. Hong Kong

Depth	Orientation	South	East	North	West
0.6m	**Reduction(kWh)**	96437.69	117250.88	92758.31	117821.16
	Proportion	1.24%	1.50%	1.19%	1.51%
0.8m	**Reduction(kWh)**	94868.81	116564.44	90690.25	117166.22
	Proportion	1.22%	1.49%	1.16%	1.50%
1m	**Reduction(kWh)**	92709.53	88709.25	88287.72	88872.44
	Proportion	1.19%	1.14%	1.13%	1.14%

3. Miami

Depth	Orientation	South	East	North	West
0.6m	**Reduction(kWh)**	133372.09	140007.00	132389.69	142196.25
	Proportion	1.71%	1.79%	1.70%	1.82%
0.8m	**Reduction(kWh)**	132674.06	139712.13	131597.16	142196.25
	Proportion	1.70%	1.79%	1.69%	1.82%
1m	**Reduction(kWh)**	131756.41	129854.81	130297.78	131949.78
	Proportion	1.69%	1.66%	1.67%	1.69%

4. Houston

Depth	Orientation	South	East	North	West

0.6m	**Reduction(kWh)**	132910.97	139778.84	131044.81	141233.09
	Proportion	1.70%	1.79%	1.68%	1.81%
0.8m	**Reduction(kWh)**	131986.97	139392.09	128393.78	140950.69
	Proportion	1.69%	1.79%	1.65%	1.81%
1m	**Reduction(kWh)**	130793.47	127876.66	128393.78	129928.31
	Proportion	1.68%	1.64%	1.65%	1.66%

From Table 6.4 it is clear that lighting energy reduction in Miami and Houston is higher than that in Hong Kong and Singapore. Comparing the data in Table 5.4 with above tables, it is clear that daylighting performance of overhang equipped window is almost the same as the daylighting performance of double-layer glazing and low-e glazing. Daylighting performance of interior blind is the worst within all envelope design measures studied.

It is also clear that performance of daylighting strategy on east and west orientations is better than that on south orientation, but the difference is decreasing with the latitude rises. Daylighting performance on north orientation is the worst, but as the latitude rises, the difference becomes less significant.

As depth increases, daylighting performance of the overhang becomes worse. The decrease in daylighting performance is significant on east and west orientations. While on south and north orientations, the decrease is not very significant. When the overhang depth changes from 0.6m to 1m, daylighting performance on south and north orientations drops at less than 2% in most cases, while performance on east and west orientations drops at more than 8% in most cases. As the latitude rises, the performance reduction on east and west orientations becomes smaller. In Hong Kong, when the overhang depth changes from 0.6m to 1m, daylighting performance on east and west orientations even drops more than 20%. While in Miami, when the overhang depth changes from 0.6m to 1m, daylighting performance on east and west orientations only drops around 8%.

6.4 Comprehensive Evaluation Considering both Thermal and Daylighting Performances

6.4.1 Evaluation of Glazing Materials

As discussed in Chapter 4, in cooling dominant area applying energy efficient glazing on building envelope can reduce heat gain through window area. Since almost all of the heat gain through window area is radiation heat gain that travels directly through transparent glass area, thermal resistance of glazing material cannot affect the window thermal performance. The key factor that affects window thermal performance is the solar transmittance of glazing materials. Application of double-layer glazing could reduce window heat gain at about 15% to 20%. Application of low-e glazing could receive an even further reduction. While low-e glazing with a solar transmittance of 0.4 is applied, the window heat gain reduction could be as much as 50%. As shown in Table 6.2, daylighting performance of low-e glazing stays almost the same as that of double-layer glazing. Considering low-e glazing has a better thermal performance than double-layer glazing, low-e glazing is a better choice for energy-efficient design and retrofitting measure than double-layer glazing in cooling-dominant area.

It is also clear from previous discussion that both thermal and daylighting performances of advanced glazing material are better on east and west orientations. Both thermal and daylighting performances on north orientation is the worst. Advanced glazing materials perform better in hotel and shopping mall buildings than that in office buildings.

6.4.2 Evaluation of Shading Devices

For interior blind, as shown in Chapter 4 its application could significantly reduce window heat gain in cooling-dominant climates. According to previous simulation result, interior blind installation could help reduce window heat gain for around 20%, and the thermal performance of blind decreases with the decrease of reflectivity. As presented in Figure 6.1, daylighting performance of interior blind also decreases with the louver's reflectivity. The impact of occupant's behavior on blind's performance also gets smaller as the reflectivity rises. Thus it is clear that the louver's reflectivity is the key factor that affects the blind's comprehensive performance. The higher the reflectivity is, the better the blind performs.

For overhang, as shown in Chapter 4 a reduction of around 40% in window heat gain could be received with the application of overhang. As the depth gets longer, the thermal performance gets better. As presented in Table 6.4, daylighting performance drops as the depth increase. As overhang's depth changes from 1m to 0.6m, its thermal performance drops at 20%, while its daylighting performance drops at 8%-10% in most cases. Depth is the key factor that affects the comprehensive performance of overhang. There exist an ideal depth so that the overhang could block out large amount of solar radiation while still retain an acceptable amount of daylight.

According to previous simulation result in Chapter 4, the thermal performance of overhang is better than interior blind while louver's tilt angle is 90°. Reducing the tilt angle could only make the difference smaller. As shown in Table 6.3 and 6.4, the daylighting performance of overhang is also better than interior blind. As the tilt angle decreases, the blind's daylighting performance gets weaker. Thus it is clear that considering the comprehensive performance, overhang is a better shading choice than interior blind in cooling-dominant area.

Orientation is an important issue that affects shading device's performance. As discussed previously, shading device performs about 20% better on east and west orientation. After equipped with shading device, daylighting strategy applied on east and west orientations also performs better. On north orientation, both thermal and daylighting performances are the worst. On east and west orientations, the impact of depth on overhang performance is quite clear, while on south and north orientations, the impact is insignificant.

Location could also affect the shading device's performance. Although there exist difference in both thermal and daylighting performance on different orientations, as the latitude rises, the difference becomes smaller. The impact of depth on overhang also decreases as the latitude rises.

6.5 Summary

In this chapter, the daylighting performance of several popular energy-efficient design measures on window area of commercial building envelope has been simulated and discussed. The factors that may affect the daylighting performance are investigated. A comprehensive evaluation is also conducted to assess the total energy performance of the design measures.

After application of daylighting strategy, energy will be saved from artificial lighting system. Lighting energy saved on double-layer glazing is almost the same as that on low-e glazing. Considering low-e glazing could reduce more window heat gain than double-layer glazing, low-e glazing application should be the first choice during building design and retrofitting process in cooling-dominant area.

Orientation and geography location are important factors that affect the glazing material's performance. On east and west orientations, glazing performs better, while in north orientation, the performance is the worst. In cooling-dominant area with low latitude, the difference among different orientations is quite obvious. As the latitude rises, the difference becomes insignificant.

Interior blind with higher reflectivity has better daylighting and thermal performance. The impact of occupant's behavior becomes insignificant as the reflectivity rises. Interior blinds on east and west orientations have better daylighting and thermal performance, while blind on north orientation performs the worst. In cooling-dominant area with low latitude, the difference among different orientations is quite obvious. As the latitude rises, the difference becomes insignificant.

The comprehensive performance of overhang is better than that of interior blind. Thus during design and retrofitting of building envelope, overhang shading should be considered first. Overhangs on east and west orientations have better daylighting and thermal performance, while overhang on north orientation performs the worst. In cooling-dominant area with low latitude, the difference among different orientations is quite obvious. As the latitude rises, the difference becomes insignificant. Depth is a key factor that affects the overhang’s performance. There exists an ideal depth to maximize the overhang’s performance. As latitude rises, the ideal depth could be larger. On east and west orientations, the impact of depth on overhang performance is quite clear, while on south and north orientations, the impact is insignificant.

Chapter 7

Thermal Performance of Insulation against Walls

7.1 Introduction

As mentioned in Chapter 2, in regions with high latitude space heating is necessary during cold winter, the highest temperature difference between indoor space and outside environment could be much as 15℃~20℃. While in cooling-dominant area, temperature difference between indoor space and outdoor environment during air-conditioning hours is just around 8℃. Due to this divergence, conventional building design in low latitude area does not consider building envelope insulation as an important issue. Previous researches on high reflectivity surfaces mainly focused on roof area, when it came to vertical wall area, reported studies were very limited. Also previous researchers mainly focus on the effect of improving the reflectivity of roof surface, seldom studied the different effects of increasing roof reflectivity and thermal resistance. Studies on thermal insulation application in low latitude climate regions are very limited. Insulation installation for cold climates is aimed at reducing surface convection. The effects on vertical walls of different orientations are often overlooked justifiably. For cooling requirement dominating climate regions, thermal insulation and high reflectivity coating may have interchangeable functions, and yet they may produce savings of different magnitudes on walls of different orientations.

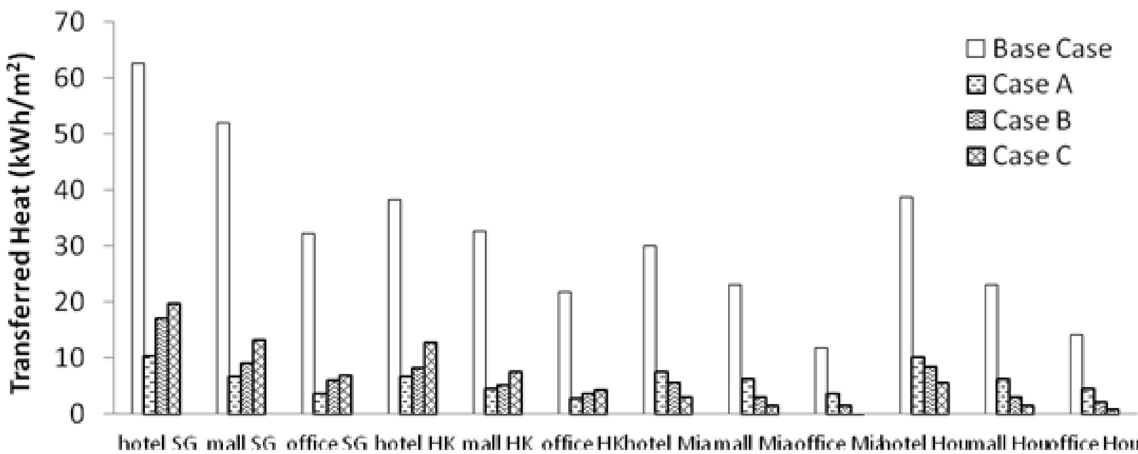
In this chapter, with the application of popular building energy simulation software EnergyPlus, the effects of thermal insulation and high reflectivity treatment on the air-conditioning cooling load in cooling-dominant area is numerically studied. Two most commonly applied energy-efficient insulation measures, namely extra insulation material installation and high-reflectivity coating application are selected. The impact of different orientations, climate as well as different installation position are also simulated and discussed.

7.2 Energy Performance

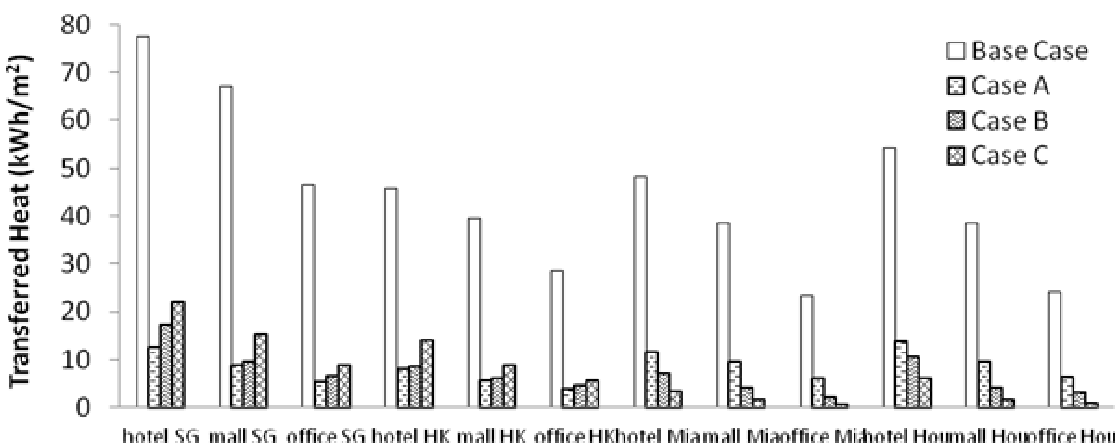
7.2.1 Overall Energy Performance

For external wall surface insulation installation, the commonly utilized XPS (extruded polystyrene) board was selected. The board was 50mm thick. The conductivity was 0.035 W/m•K. The specific heat was 1470 J/kg•K. Two installation methods, attachment to either external or internal surfaces of the wall, will be compared. For high-reflectivity coating, a product widely used in Europe was taken as a reference. The main component of this product was environmental friendly acrylic polyurethane, and the reflectivity was 0.89. It should be particularly noticed that besides high-reflectivity coating, using a layer of shading material is another alternative. It shares the same principle of reducing the radiation heat gain through reducing the radiation heat projected on the surface. Thus in this research, high-reflectivity coating will also shed light on the effectiveness of wall external shading.

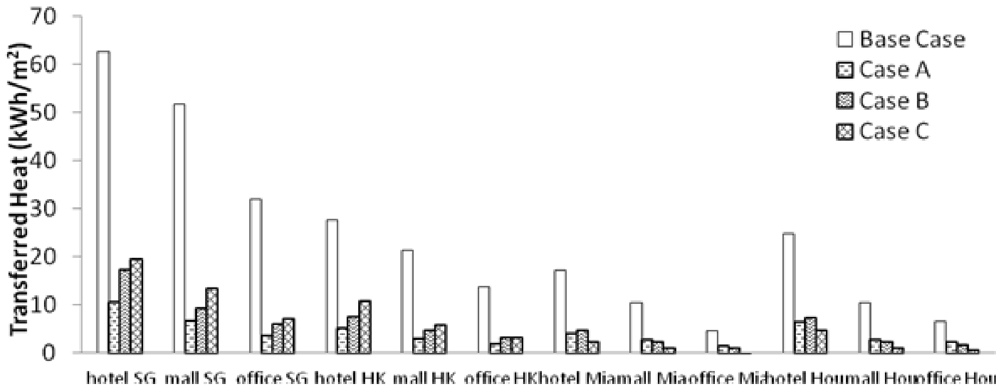
The annual total heat transfers per unit wall area of each orientation are presented in Figure 7.1. It should be noticed that in the following figures, Base Case stands for the original building envelope design. Case A stands for insulation installation on the interior surface of the wall, Case B for insulation installation on external surface of the wall, Case C for high-reflectivity coating application.



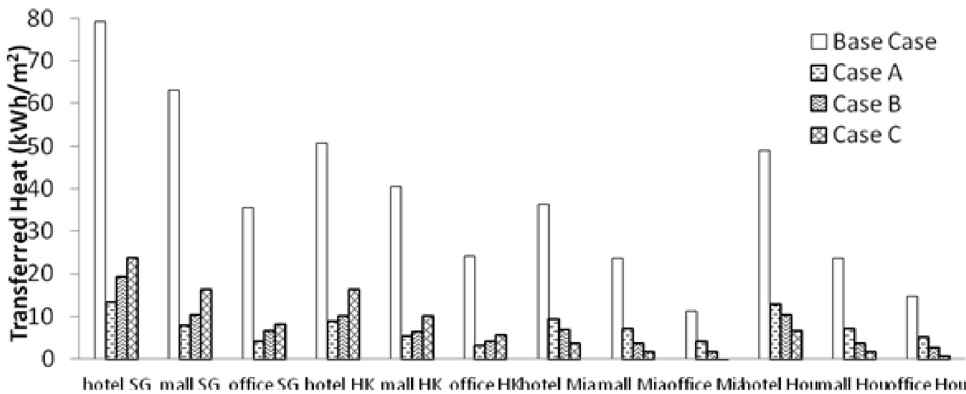
1. Effects on south wall



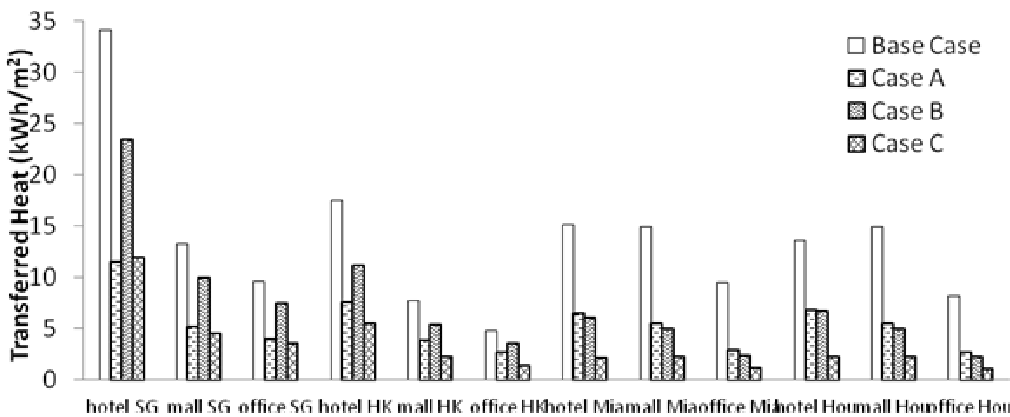
2. Effects on east wall



3. Effects on north wall



4. Effects on west wall



5. Effects on roof area

Figure 7. 1 Detailed annual energy performances of different insulation measures

It should be noted that heat transferred through wall area cannot be considered as the instant cooling load. Part of it should be absorbed by other surfaces through radiation first, and then released to the space through convection. In this paper, the simulation period is one year. In such a long period, we could consider that the heat gain through wall area and the space cooling load caused by heat gain through wall area is consistent.

Taking Case C in Hong Kong office building for an instance, applying high-reflectivity coating on Hong Kong office building external wall area could reduce about 3.15×10^5 kWh heat gain through building external wall area. The monthly difference between heat gain reduction and building total cooling load reduction is presented as follow:

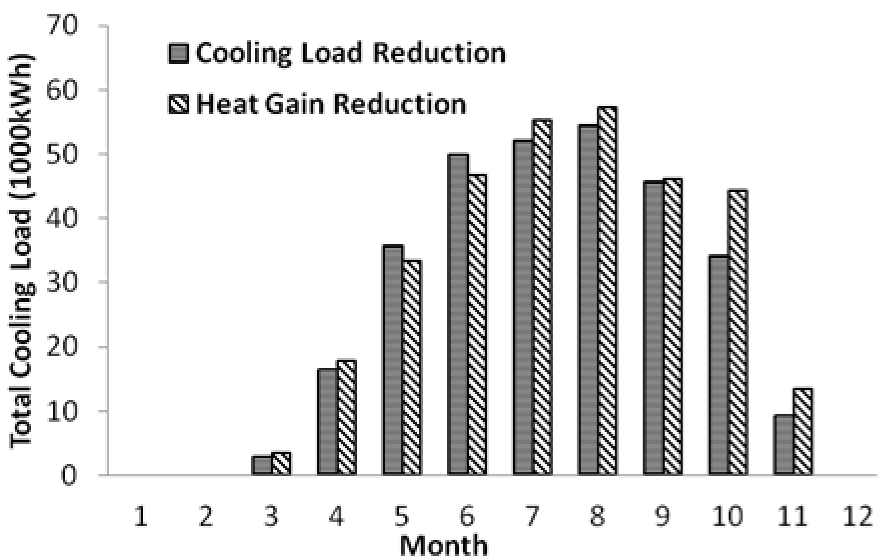


Figure 7. 2 Difference between total cooling reduction and transfer heat gain reduction in Case C

The total cooling reduction in Case C is around 2.95×10^5 kWh. The difference is very small. It could be concluded from Figure 7.1 that, in all cases, all the three insulation measures could significantly reduce AC system load caused by heat transferred from envelope wall area. In most cases, cooling load could be reduced as much as 80%, some even exceed 90%. It could also be observed that, due to their longer operation hours, hotel and shopping mall buildings get much more heat through building envelope than office buildings, but the reduced proportion does not change significantly within all 3 building types.

It is commonly known that due to its relatively low thermal resistance and transparency, heat gain through window area accounts for a large proportion in the overall heat gain through building envelope. Thus in most cases, window area is equipped with different sorts of shading systems. In this simulation, simple shading such as curtains is applied on window area so that heat gain through window area could be reduced. To better quantify the cost-effectiveness of the wall-retrofit measures, the heat gain reduction of different wall-retrofit measures on envelopes facing different orientations and their proportions in the total envelope area heat gain are calculated for Hong Kong.

In the base case, the annual heat gain through all the wall areas and through the whole building envelope (including both windows and walls) are represented as W and G (kWh) respectively. The annual heat gain reduction wall retrofit on a single orientation is defined as m (kWh). Then we define two percentages δ and γ as follows:

$$\delta = \frac{m}{W} \times 100\% \tag{7.1}$$

$$\gamma = \frac{m}{G} \times 100\% \tag{7.2}$$

Detailed data of δ and γ in the city of Hong Kong are presented in Table 7.1.

Table 7. 1 Effects on the total heat gain of the envelope of different orientations in Hong Kong

1. Hotel

Orientation	Case A			Case B			Case C		
	m(kWh)	δ	γ	m(kWh)	δ	γ	m(kWh)	δ	γ
South	125801	15.6%	5.2%	121313	14.8%	5.0%	100447	12.5%	4.2%
East	152883	18.4%	6.4%	150156	18.1%	6.2%	126943	15.5%	5.3%
North	89432	11.1%	3.7%	78654	9.9%	3.3%	62512	8.3%	2.6%
West	169437	20.5%	7.0%	166306	19.9%	6.9%	139360	16.9%	5.8%
Roof	99146	11.7%	4.1%	63540	7.5%	2.6%	120450	14.2%	5.0%
Total	636700	77.2%	26.3%	579971	70.2%	24.0%	549715	67.5%	22.9%

2. Shopping mall

Orientation	Case A			Case B			Case C		
	m(kWh)	δ	γ	m(kWh)	δ	γ	m(kWh)	δ	γ
South	111876	18.5%	5.0%	111495	18.0%	5.0%	101699	16.5%	4.5%
East	137429	22.2%	6.1%	136556	22.0%	6.1%	125846	20.2%	5.6%
North	72811	12.0%	3.2%	65831	11.0%	2.9%	58227	10.2%	2.6%
West	142315	23.1%	6.3%	140622	22.5%	6.3%	124538	20.0%	5.5%
Roof	38396	6.1%	1.7%	23895	3.8%	1.1%	55245	8.7%	2.5%
Total	502827	81.9%	22.3%	478398	77.2%	21.4%	465554	75.6%	20.7%

3. Office

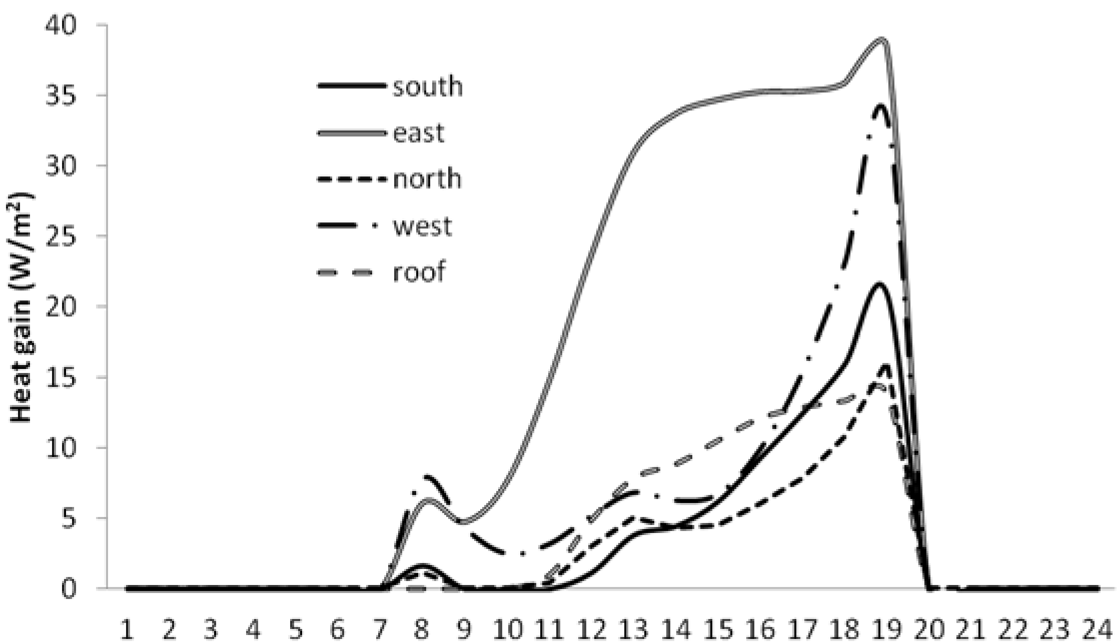
Orientation	Case A	Case B	Case C

	m(kWh)	δ	γ	m(kWh)	δ	γ	m(kWh)	δ	γ
South	76095	19.1%	4.5%	73122	18.2%	4.3%	71997	17.5%	4.2%
East	100804	25.0%	5.9%	98447	24.3%	5.8%	93539	23.2%	5.5%
North	47021	12.1%	2.8%	41197	10.7%	2.4%	39019	10.7%	2.3%
West	84934	21.2%	5.0%	81118	20.0%	4.7%	74863	18.7%	4.4%
Roof	21260	5.1%	1.2%	12601	3.0%	0.7%	35194	8.5%	2.0%
Total	330114	82.6%	19.4%	306482	76.2%	17.9%	314611	78.5%	18.4%

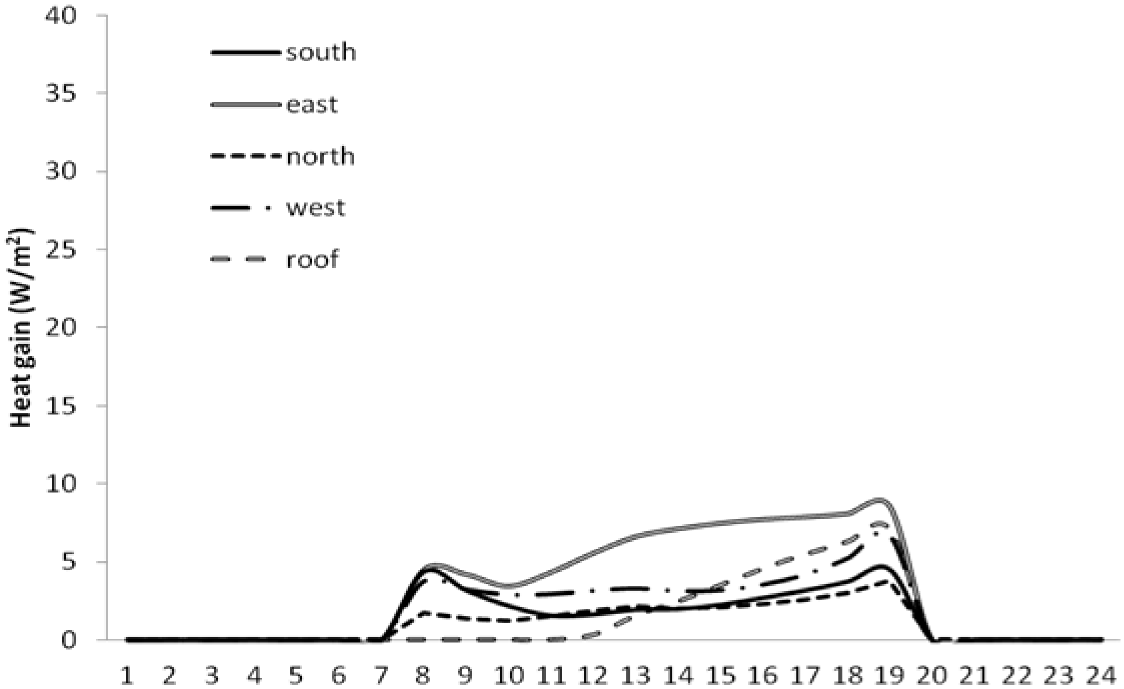
From Table 7.1 it is clearly seen that even if window heat gain is taken into account, wall treatment on some building envelopes could still achieve a considerable reduction on the total heat gain. It could also be concluded that due to different proportions that wall surfaces facing different orientations take, insulation on different facades could receive different effects. With the same wall surface area involved, insulation on east and west walls receives the largest profit, followed by south wall. While applying insulation on north wall will only receive about half on heat gain reduction, comparing to other wall surfaces. When it comes to roof area, although it gets the largest area, its profit after insulation is the least. Similar conclusion could also be achieved in Singapore, Miami and Houston.

It should be noted that all the values in Table 7.1 is only applicable for this particular simulation model. In this model building, the envelope surface area to floor area ratio is relatively small. Different results could be achieved according to different building shapes.

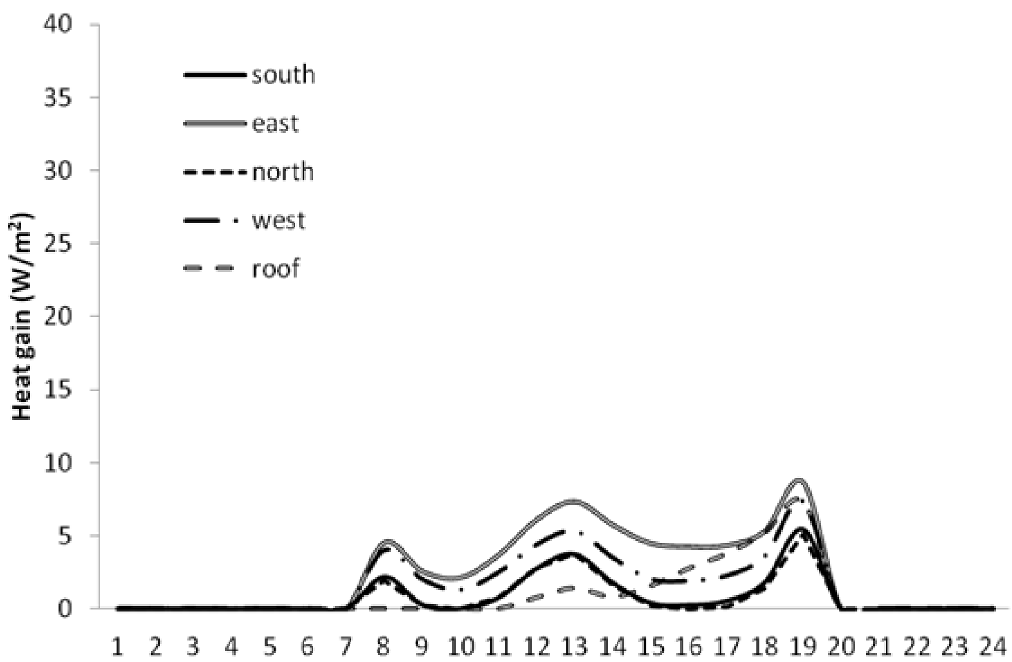
Another contribution of the insulation measures is the reduction of peak transfer heat. Due to the relatively stable inner heat source, the peak system cooling load lies largely in the peak transfer heat through building envelope. The reduction of peak cooling load could help reduce the cost of HVAC system operation and relieve the pressure of electricity supply. Figure 7.3 gives the transfer heat data of office building in Miami in a typical summer day, the reductions of peak transfer heat in all 3 cases are presented. Compared with base case, it is quite clear that in all 3 cases the peak transfer heat through wall area is largely reduced, which would no doubt contribute to the reduction of peak cooling load.



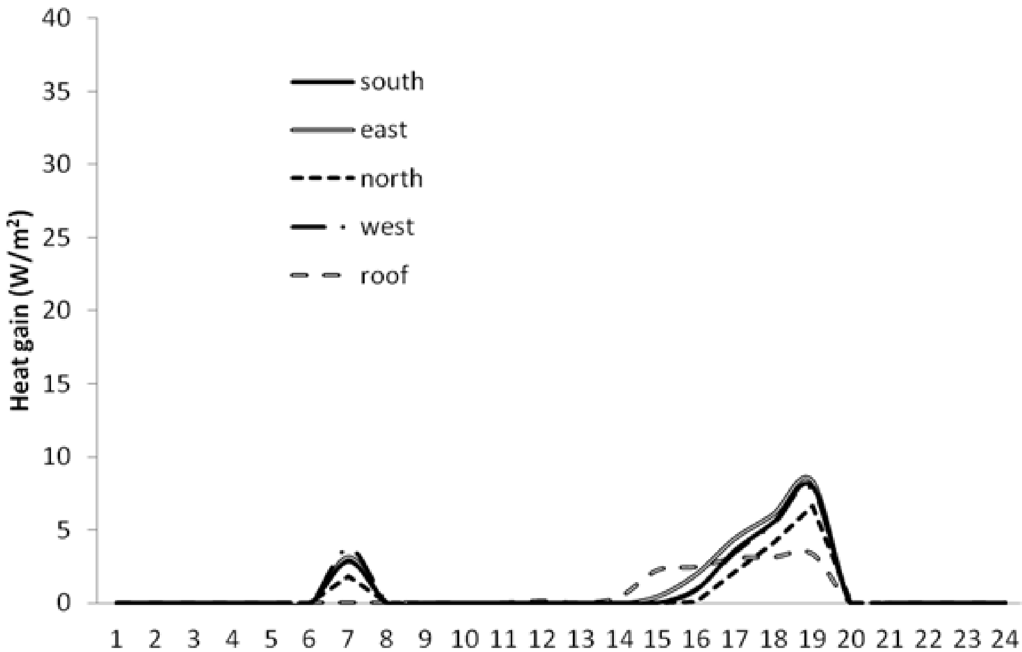
1. Base Case



2. Case A



3. Case B



4. Case C

Figure 7. 3 Peak transfer heat changes in Miami office building in a typical summer day

7.2.2 Impact of Orientation

In previous studies, researchers tend to consider the building envelope as a whole and discussed the performance of different energy-efficient measures. In order to analyze the impact of orientations, in this research heat transfer on different building facades were calculated separately.

From above discussion it is obviously that orientation could affect the profits of insulation measures, insulation on east and west wall could receive the largest profit with the same construction, while the profit of north wall insulation could be halved. The roof insulation receives the least profit although its area is larger than any other surfaces.

When it comes to the effect of different insulation measures, it is obvious from Figure 4 that on vertical wall surface, there were no significant differences of energy performance among different retrofitting measures. For a particular building type, the transfer heat reduction varies with orientations under the same climate situation, but the percentage is stable.

On horizontal surface such as roof area, there was a slight difference. It could be concluded that under all circumstances, high-reflectivity coating always performs better than insulation. There are two reasons for this result. One reason is that radiation projection on roof area is relatively high compared to vertical building surfaces, for it is the only building surface that could receive direct solar radiation throughout the day. Taking Hong Kong as an example, Figure 7.4 gives the monthly average direct solar radiation intensity on different building facades throughout the year in Hong Kong. It is obvious that annual solar radiation projected on roof area is larger than all other surfaces, which makes high-reflectivity coating perform better on roof area. Another reason is that the building roof.in the base case already got a certain degree of insulation, which makes the effect of extra insulation not as obvious as for the walls.

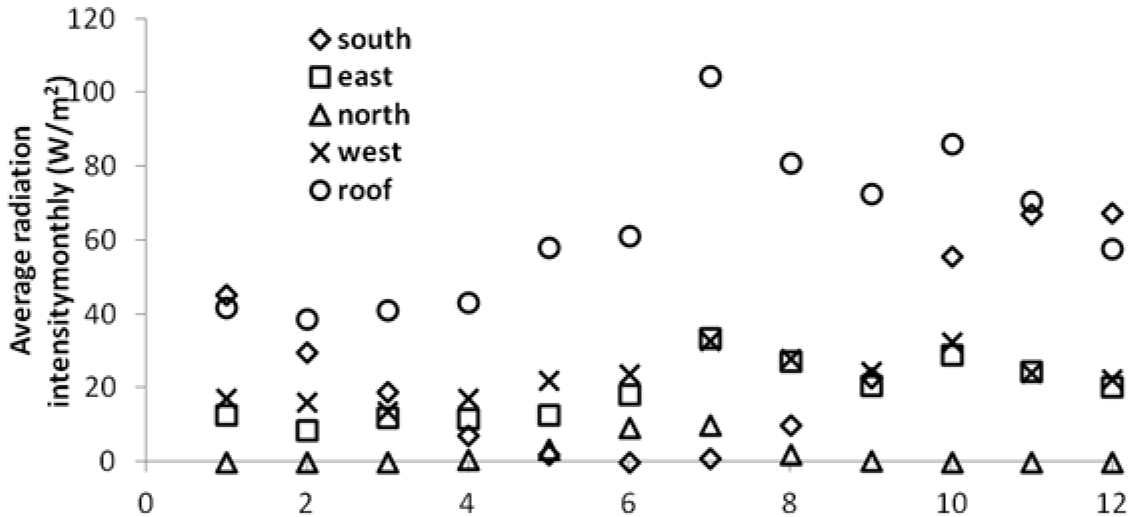


Figure 7. 4 Monthly average direct solar radiation intensity on different building facades in Hong Kong

7.2.3 Impact of Climate

Four cities, namely Singapore, Hong Kong, Miami and Houston were selected to observe the impact of climate. It is clear from Figure 7.1 that in Singapore and Hong Kong, extra insulation performs slightly better than high-reflectivity coating, while in Houston and Miami, high-reflectivity coating performs better. The reason lies in the radiation intensity difference. As shown in Figure 7.5, annual total solar radiation level in Houston and Miami is higher than that in Hong Kong and Singapore. The calculation result indicates that in area with high level of solar radiation, the high-reflectivity coating could contribute to cooling load reduction more significantly, regardless different orientations.

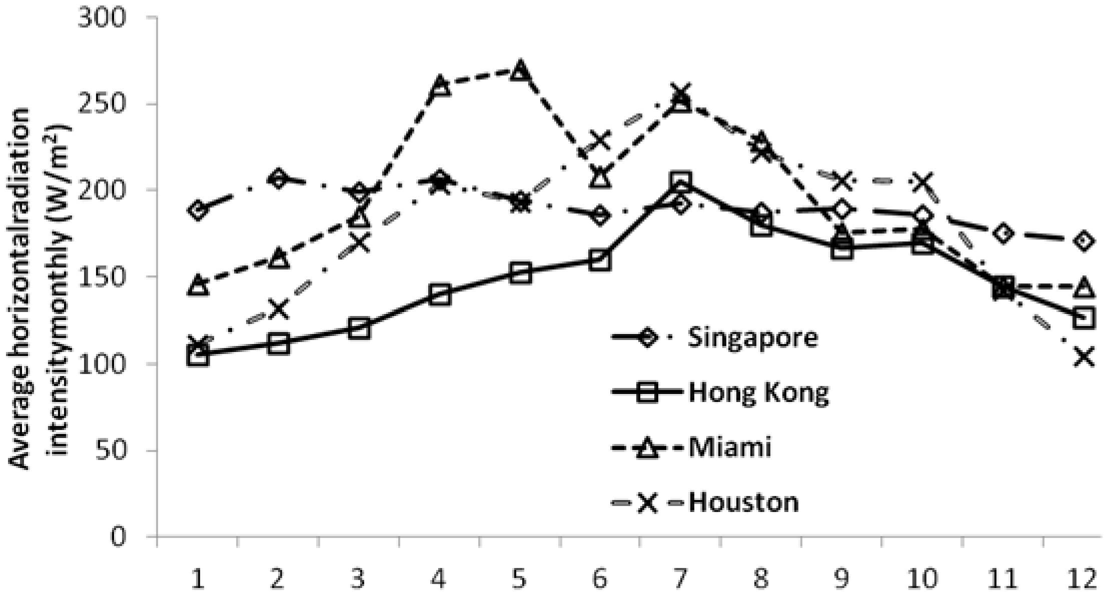


Figure 7. 5 Total solar radiation intensity levels of different cities

It could also be concluded from Figure 7.1 that in Singapore and Hong Kong, insulation installed on interior surface of a wall performs better than that on external surface, while in Miami and Houston an opposite conclusion can be obtained. This result could mainly be attributed to the thermal storage effect of the envelope mass.

Figure 7.6 and Figure 7.7 respectively give the temperature and the horizontal solar radiation changes over time during a clear sunny day in July in these four cities.

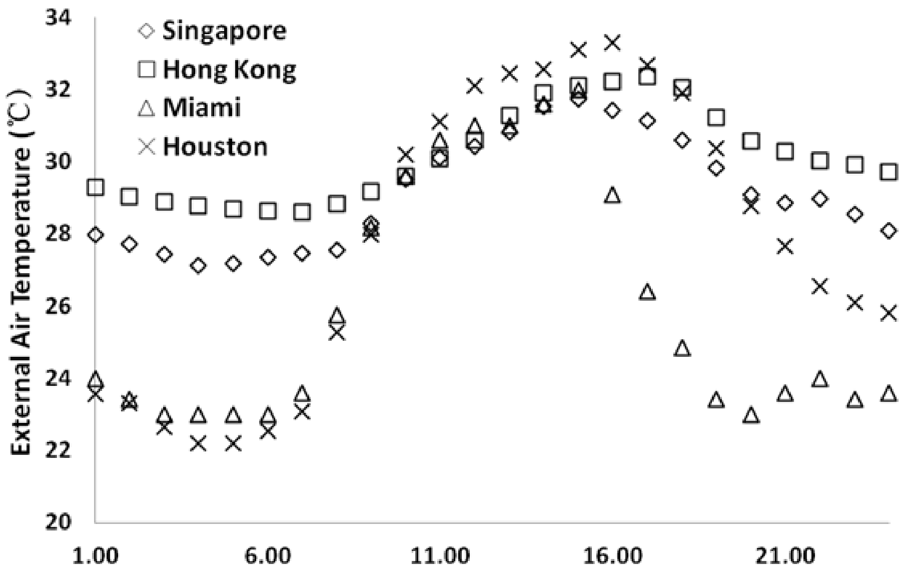


Figure 7. 6 Temperature changes over time during a typical summer day in four cities

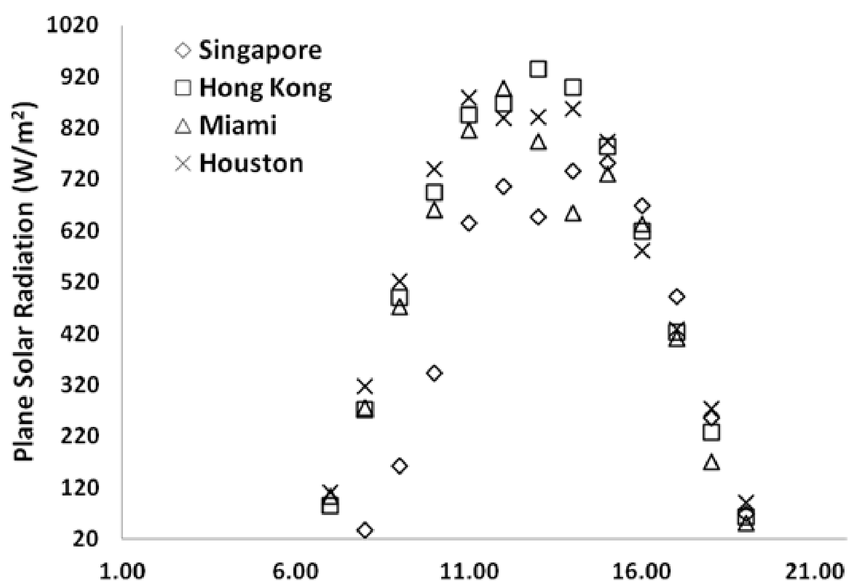
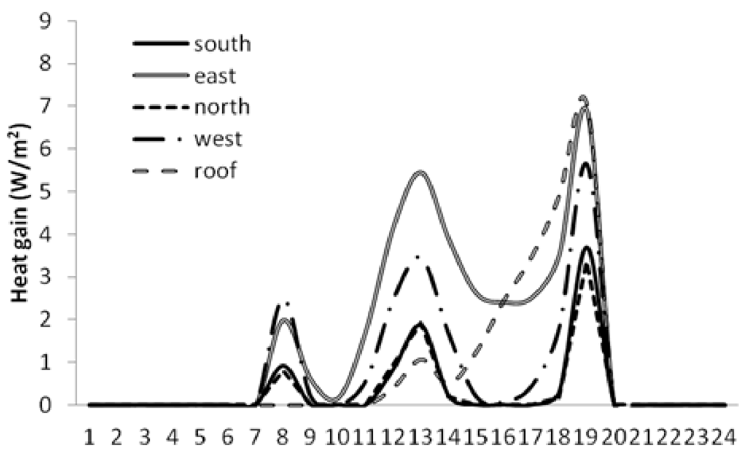


Figure 7. 7 Horizontal solar radiation changes over time during a typical summer day in four cities

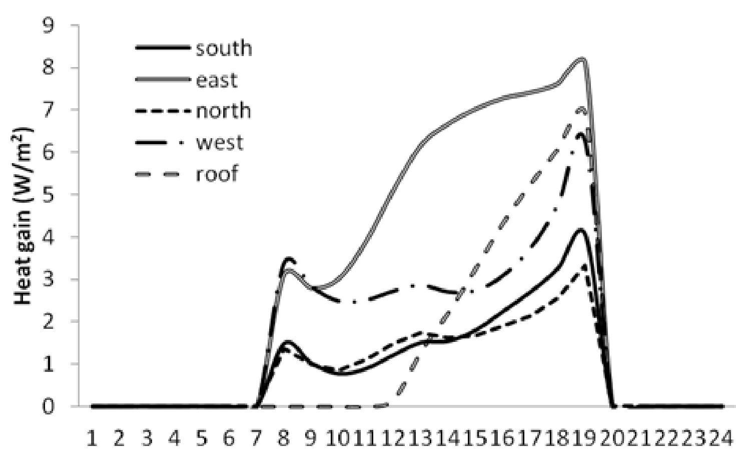
It could be observed from Figure 7.6 and Figure 7.7 that during a sunny summer day, the peak environment air temperature and solar radiation level do not vary a lot. In Singapore and Hong Kong, the diurnal temperature difference is just about 3 to 4℃, while in Houston and Miami, the diurnal temperature difference could be as large as 10 ℃.

In cities like Houston and Miami, temperature at summer night could be 8 to 10 degrees Celsius lower than daytime, and even lower than the temperature set point of air-conditioning. The relatively cool external environment could serve as a perfect cold source for building envelope. During daytime, building envelope could absorb a considerable part of heat gain from external environment. Placing insulation on external surface of building envelope could maximize the use of thermal inertia of building envelope. In cities like Hong Kong and Singapore, the situation is different. Since the night ambient temperature is higher than the air-conditioning set-point on the summer days, placing in the insulation on interior surface of the wall can reduce the heat stored from the night contribution. But in the transient seasons, the effect would be similar to Houston situations. All in all, interior or exterior insulation makes little differences in Hong Kong.

The thermal storage effects can be best understood by observing the hourly cooling load variations on a typical day. Figure 7.8 and Figure 7.9 present the hourly heat gain of an office building in Houston and Hong Kong respectively during the same typical summer day. It is clear in Figure 7.8 that, at the first a few hours after the AC system starts to operate, heat gain through the walls in Case 2 is higher than that in Case 1, while in Figure 7.9, the first a few hours after the AC system starts to operate, heat gain through the walls in Case 2 is lower than that in Case 1.

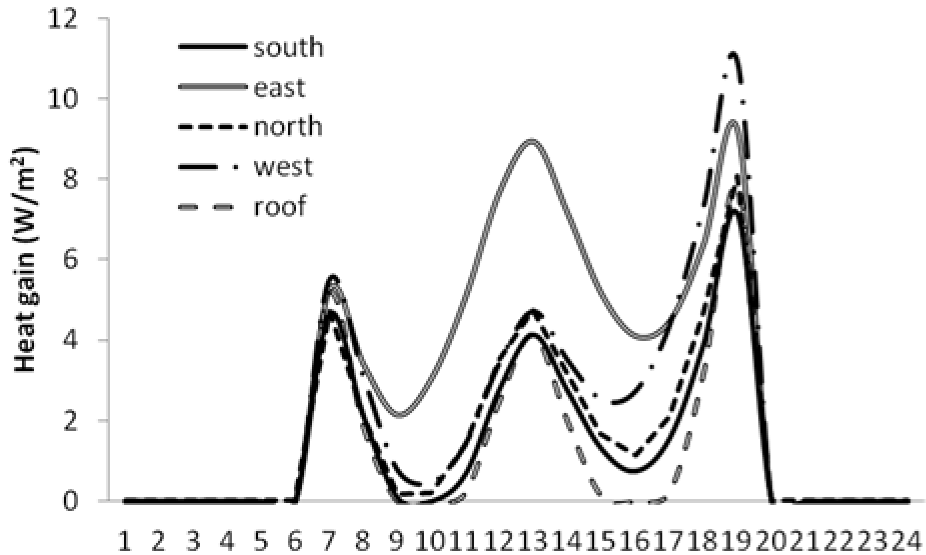


1. Insulation on external surface

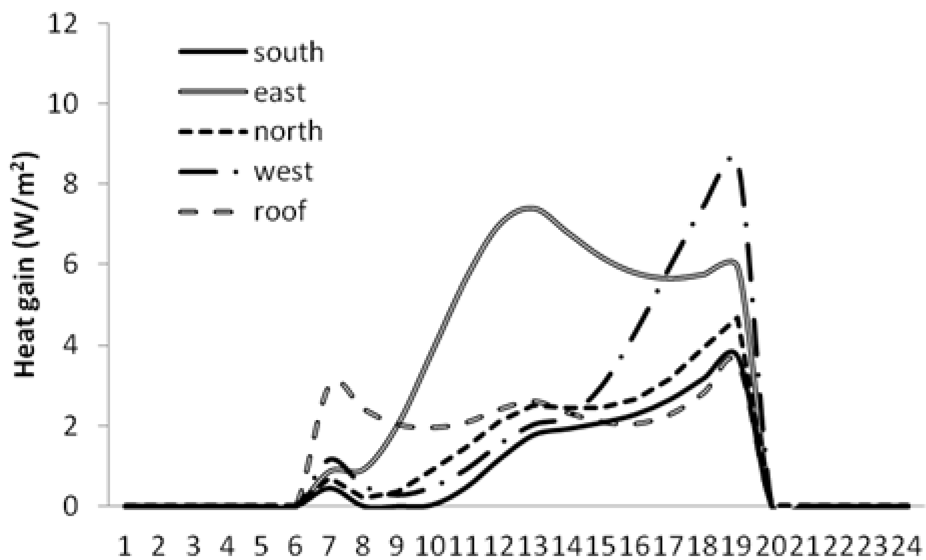


2. Insulation on inner surface

Figure 7. 8 Heat gain through building envelope in a Miami office in typical summer day



1. Insulation on external surface



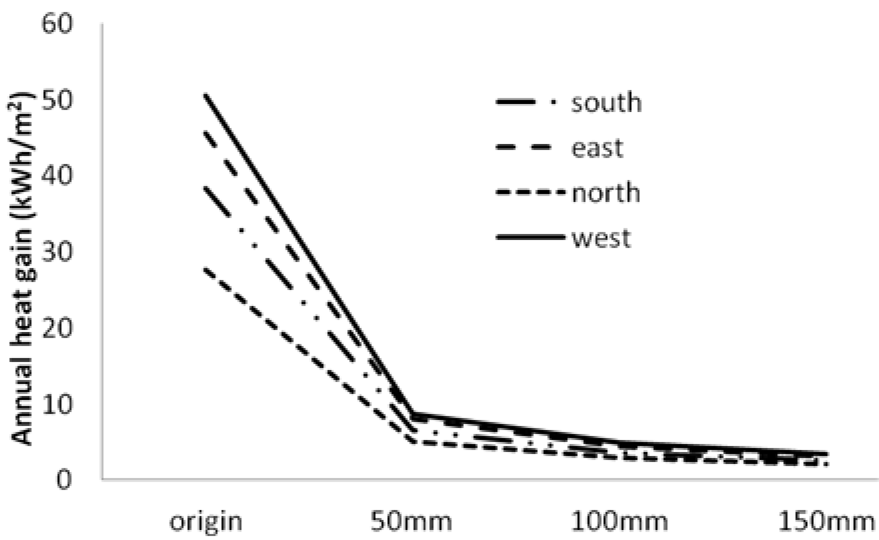
2. Insulation on inner surface

Figure 7. 9 Heat gain through building envelope in a Hong Kong office in typical summer day

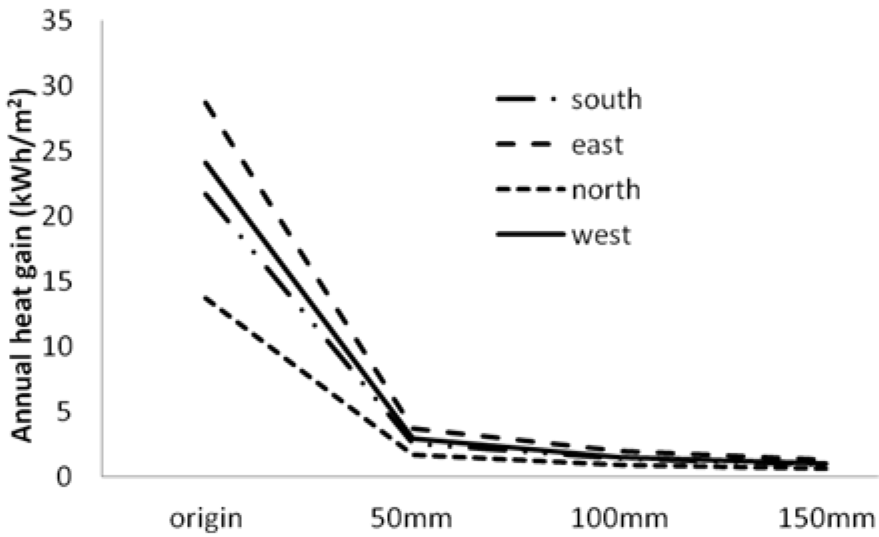
7.3 Economic Consideration

7.3.1 Impact of Thickness on Insulation Performance

From above discussion, it is already clear that an installation of 50mm thick insulation board could reduce system cooling load caused by heat gain through building envelope significantly. In the simulation study, the thickness of insulation material was also considered. Figure 7.10 gives details about annual energy performance of building envelope vertical surface after installation of 50mm, 100mm and 150mm of insulation board on the inner surface of envelope wall in Hong Kong.



1. Hotel



2. Office

Figure 7. 10 Performance of insulation on vertical building facades with different thickness in Hong Kong

It could be concluded that although thicker insulation could reduce more heat gain through envelope wall area, the contribution is relatively small. Increasing insulation thickness to 100 mm or 150 mm would only bring in an extra reduction of less than 10% in most cases. Same conclusion could also be received in result of other cities.

7.3.2 Impact of Declined Reflectivity on Coating Performance

Due to its direct exposure to the environment, high-reflectivity coating could easily suffer from a serious reduction of reflectivity. If the painted surface is not washed regularly, the reflectance could drop rapidly. The aged reflectance of coating without washing after two years could be expressed as follows (Hong Kong Government, 2007):

$$\text{Aged Reflectance} = 0.7 \cdot (\text{Initial Reflectance} - 0.2) + 0.2 \tag{7.3}$$

Figure 7.11 gives annual energy performance of an office building envelope in Hong Kong with high-reflectivity coating application in three years if the surface is not washed regularly.

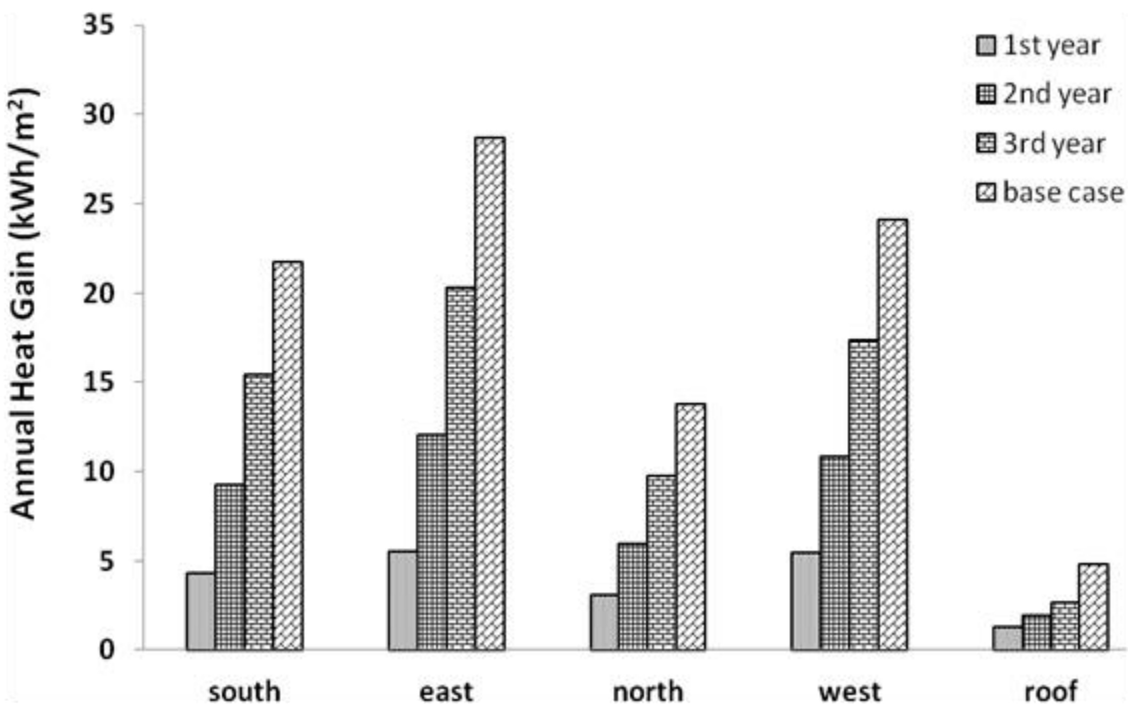


Figure 7. 11 Impact of declined reflectivity on energy performance of coating

Decline of reflectance could seriously affect the performance of high-reflectivity coating. A regular maintenance is necessary to keep the painted area stay effective. Literature also claimed that with simple water wash, the coating could retain its reflectance satisfactorily (Suehrcke et al., 2008).

7.4 Summary

In this chapter, a simulation research was conducted to investigate performances of two most popular energy-efficient insulation measures, installation of extra insulation material and application of high-reflectivity coating on commercial building external wall area. Three typical commercial building were selected, namely office, hotel and shopping mall. Performances of insulation measures on different building facades were examined separately. Different installation positions of insulation were also considered. Four cities with different climates were selected to investigate the impact of climate on performances of different insulation measures.

In cooling-dominant climates, application of extra insulation and high-reflectivity coating on building envelope wall area could significantly reduce AC system cooling load caused by heat gain through building envelope in commercial buildings, even if heat gain through window area is considered.

The orientation could affect the profits of insulation designs significantly. Insulation on east and west walls performs best with the same wall area construction involved, while north wall insulation only receives half the profit. When it comes to roof area, the profit is the least profit. The orientation of vertical building facades makes little affect on performances of different insulation measures. But in roof area, due to relatively high solar radiation projection, the high-reflectivity coating always performs better than extra insulation. Performance of high-reflectivity coating is affected by local radiation level largely.

In area with a large temperature difference between daytime and nighttime, insulation installed on external building surface performs better, while in area with relatively small temperature difference, insulation installed on inner building surface performs better. The reason causing this phenomenon is the heat storage ability of building façade. Appropriate application of thermal inertia of building envelope could improve the performance of insulation.

Some economy issues are also discussed in this paper. Application of 50 mm thick insulation board could receive a satisfactory result. However, increasing thickness to 100 mm or 150 mm could only receive a very limit additional profit. Thus selection of insulation thickness should be very careful so that a maximum profit could be expected. Besides, reflectance declining could serious affect the performance of high-reflectivity coating. A regular washing maintenance is necessary for keeping the coating efficient.

Further work would be focused on other advanced energy-efficient design and retrofitting measures on building envelope in cooling-dominant climates. Performance of different shading equipment and glass materials under different building orientations as well as climates is also a very interesting issue. The result could also serve as very useful reference for practical projects.

Chapter 8

Conclusive Remarks and Recommendations for Future Work

Building is the most important and indispensable part of one's life. The design of building environment has attracted a growing attention from the public, and is becoming a rapidly developing industry. Buildings consume between 40% and 60% of all energy used in most developed economies throughout the world. Correspondingly, they are responsible for a similar proportion of humankind's carbon dioxide emissions with a consequential impact on global warming and an increasing proportion in many developing and emerging economies. With a further development of economy and urbanization, the proportion of building energy consumption is likely to keep growing rapidly, which could be a serious problem. Building energy management is considered to be one of the most direct and effective way to relieve the energy shortage. It is not hyperbole to suggest that a better design of buildings can significantly reduce energy consumption of the whole world, and contribute to environmental impact and climate change. In order to achieve a good energy management in buildings, the building energy simulation plays an important role.

Building energy simulation focuses on those thermal systems which are parts of a building or interact with the building as well as build environment. In a building energy simulation, prediction of thermal response of a building and performance of the air-conditioning systems requires modeling of the heat and mass transport processes which take places in the building and the systems, so that proper design decision can be made.

In this study, a series of simulation studies were conducted to investigate the comprehensive thermal and daylighting performance of several popular energy-efficient design measures on commercial building envelopes in cooling-dominant areas. Energy saving from different design measures were calculated and discussed. The impacts of different thermal and structure parameters were analyzed. Impacts of orientation and location were considered. A deeper and better understanding of commercial building enveloped designs in cooling-dominant area is obtained. The research findings can be concluded into following results and future research works.

8.1 Conclusions

Building envelope can be considered as the most important element in buildings. Energy consumed by building envelope takes a large part during the building's life cycle. The design of building envelope is a large and hot research area all over the world.

In area with high latitude, heating is required in winter. During the heating period, the temperature difference between indoor and outdoor can be as large as 20℃. Under this condition, insulation against building envelope is necessary. Traditionally, more attention is paid on building envelope under cold climates. Conventionally, building envelope is lightweight with the consideration that heat could be diffused easily in cooling-dominant areas. Studies on thermal performance of building envelope in cooling-dominant areas are very limited.

Daylight is considered to be the best light source. Application of daylighting can receive a comfort visual environment, which will improve occupant's satisfactory and working efficiency. Daylighting design can also reduce energy consumption from artificial lighting system.

The purpose of this research is to make a comprehensive evaluation on several popular energy-efficient design measures of building envelope in cooling-dominant areas. The key findings are listed as follows:

- In cooling-dominant climates, application of extra insulation and high-reflectivity coatings on building envelope wall area can significantly reduce AC system cooling load caused by the heat gain through building envelope in commercial buildings, even if heat gain through window area is considered. With respect to transparent insulation against window area, though the thermal resistance of window glazing cannot help to reduce the window heat gain, the shading effect of double-layer glazing and low-e glazing can block out unwanted solar radiation. The application of interior blind and overhang can also significantly reduce heat gain through window area. Besides, these designs can retain the sight view of high-rise commercial buildings at a relatively high level, which is a very important factor in building design and retrofitting.

- The orientation is an important factor that affects the performance of building envelope designs. For insulation against wall area, insulation applied on the east and west walls performs best with the same wall area construction involved, while the north wall insulation only receives a half profit. On the roof area the profit is the least. The orientation of vertical building facades makes little affection on performances of different energy-efficient envelope design measures. On roof area the high-reflectivity coatings always perform better than insulation. Performance of high-reflectivity coatings is affected by local radiation level largely. For application of advanced glazing, the proportions of heat gain reduction on different orientations do not vary significantly, but difference still exists among actual figures. Advanced glazing applied on the east and west facing façade can reduce more solar heat gain. Advanced glazing applied on the north facing façade only achieves an acceptable performance in area like Singapore where the north façade receives large amount of solar direct radiation. Similar conclusion can be achieved from the study of shading devices.
- Geography location is another factor that affects the performance of building envelope designs. For insulation against wall area, the impact mainly lies in the position of installation. In area with a large temperature difference between daytime and nighttime, insulation installed on the external building surface performs better, while in area with relatively small temperature difference, insulation installed on the inner building surface performs better. For insulation

against window area, In cooling-dominant areas not close to equator, though the south facing windows can receive solar direct radiation all day round during most time of a year, performance of the shading devices on the south façade does not vary a lot compared with those on the east and west facades. In area close to equator, effect of the north facing shading devices cannot be ignored. The performance of shading devices on the east and west facades is very stable among all cases. As the latitude rises, performance of the interior and exterior shading devices on the north façade makes small difference. But the application of shading devices on the north façade can still make an acceptable contribution to the window heat gain reduction.

- For insulation against wall area, there exists an optimum material thickness. Application of 50 mm thick insulation board can achieve a satisfactory result. As the thickness rises, the improvement is very limited.

- After application of the daylighting strategy, lighting energy saved from the double-layer glazing is almost the same as that from the low-e glazing. Considering the low-e glazing can reduce more window heat gain than the double-layer glazing, it should be the first choice during building design or retrofitting process in cooling-dominant areas. The comprehensive performance of the overhang is better than that of the interior blind.

- Orientation and geography location are important factors which affect the performance of the commercial building window designs. Energy-efficient design measures perform better on the east and west orientations, while on the north orientation, the performance is the worst. In cooling-dominant areas with low latitude, the difference among different orientations is quite clear. As the latitude rises, the difference becomes insignificant. There exists an ideal depth to maximize the overhang's performance. As the latitude rises, the ideal depth is larger. On the east and west orientations, the impact of depth on the overhang performance is quite clear, while on the south and north orientations, the impact is insignificant.

A case study involving an overhang retrofitting project on a university campus of Hong Kong was also conducted. A life cycle analysis was carried out to review the CO_2 and energy payback period of the project. The results show that though the retrofitting project can reduce more than 40% of the heat gain through window area, it takes unacceptable long time to recover the investment on the overhang system. Due to typhoon and other extreme weather condition in summer, designers tend to use a large amount of strong building materials to reinforce the external building attachments in Hong Kong, which leads to a large amount of investment.

8.2 Recommendations for the Further Work

The present research can be further extended to better understand the building envelope design under more complex condition and provide more effective designs and retrofitting measures which meet the requirement of energy-efficiency and comfort.

In this research, the model building is a single building without any neighboring ones. The influence of blocking from surrounding buildings is ignored. In the further study, a group of buildings can be considered. The thermal and visual performance can be recalculated to be more practical. In this research, the model building is a simple square building with an area of 100m × 100m. In further study buildings with more complex shape can be considered.

The focus of this research is the performance of energy-efficient design measures on commercial building envelopes. In further study, performance of energy-efficient designs on residential building envelopes can be investigated. More complex air-conditioning system can also be considered.

In this research, only several popular energy-efficient design measures were investigated. In future research, some newly developed technologies and designs can be considered. Advanced building structures such as green wall or double skin façade can be considered. The combination of building envelopes and renewable energy technologies can be studied to further reduce the building energy consumption. The thermal and visual performance of building envelopes integrated with renewable energy device can be monitored.

In this research, only the thermal and visual performances of building envelope were considered. The airflow and ventilation design is ignored. The thermal comfort of occupant is also missing. In the future research, a more exhaustive evaluation involving thermal comfort and ventilation design should be conducted.

Energy-efficient building design is a complex process. There are many factors that will affect the buildings' final performance. Only through a detailed and strict research could the target of green building be achieved. It is hoped that through this series of studies, the potential benefits of such an approach can be visible to practising designers and engineers.

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