CITY UNIVERSITY OF HONG KONG
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Daylighting Designs and Energy Performance for Air-conditioned Commercial Buildings
採光設計與空調商業樓宇能源之效益

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Abstract

Daylighting is an important factor in interior design affecting the functional arrangement of spaces, occupant comfort (visual and thermal), structure and energy use in buildings. Good quality of daylight provides not only a more attractive and pleasing atmosphere in interiors, but also creates a better indoor environment to improve working performance. From the energy and cost-saving viewpoint, the arguments for daylight are also strong. However, very little research work focusing on its energy performance has been done systemically for high-rise building development. This thesis establishes systematic methods to evaluate daylighting and its energy performance for high-rise office buildings in a dense urban area.

Building energy standards were studied and evaluated to identify salient features and useful experience. A performance-based building energy approach was adopted to evaluate daylighting and building energy performances using computer simulation techniques. A base-case office model was developed to serve as a baseline reference. To facilitate building energy analysis, a typical weather year for building energy analysis was developed and examined for Hong Kong.

Sensitivity analysis was carried out to examine the important design parameters affecting daylighting schemes. Building envelope design parameters namely window-to-wall ratio and light transmittance of windows, and height of external shadings were found significantly for predicting the energy performances, for instances annual building energy expenditure and peak electrical demands.

Detailed assessments of building energy performance due to various daylighting schemes and envelope designs were further conducted. Using regression analysis, it was found that the annual incremental electricity use, incremental peak electricity use and incremental peak cooling plant demand are a function of overall thermal transfer value and daylighting aperture. Sets of curves to indicate electricity usage and peak energy demands under different building envelope parameters were developed. Important features for daylighting schemes were highlighted and implications for OTTV designs were discussed.

In Hong Kong, many buildings are constructed close to each other and hence the external environments play a significant role in daylighting designs. This thesis investigates the shading effects due to nearby obstructions when daylighting schemes are being employed. Analysis of electricity savings was carried out for the four perimeter zones (north, east, south and west) of the whole building and individual floors. Correlations of building energy savings and the angles of obstructions were developed. It was found that shading effects due to nearby obstructions strongly affect the building energy budget when daylighting designs are used. To extend the consideration of all the design variables together (i.e. building envelope parameters and external elements), multiple regression analysis was performed. A general form of energy equations was developed to help relate building energy performance to various daylighting schemes.

Such an advanced technology can maximise the energy saving for daylighting schemes on existing commercial buildings. Recently, the thin film coatings for window glass products have been very suitable for installation of existing buildings for undertaking major refurbishment which provides a means of substantially reducing heat gain without proportionally reducing daylight transmittance. Measurements were undertaken for evaluation of the daylighting performance and energy issues (lighting and cooling) in a fully air-conditioned office using photoelectric dimming controls together with the solar control coating on the window glass. Thermal and visible properties for the window glass coupled with solar film were recorded and analysed. The findings showed that the solar film coating cut down the cooling load and decreased the energy expenditure for air-conditioning and artificial lighting systems. Energy analysis on the application of solar film coating in a reference office building using tinted glass windows with various glazing areas was demonstrated. The external obstructions together with the office building were also modelled based on a similar setting in one of the main business districts in Hong Kong. The findings can provide architects and building designers useful information for the energy saving potential of different daylighting schemes in a densely built urban city.

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List of Abbreviations and Acronyms

ACH	air change per hour
ASEAN	Southeast Asian Nations
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BECL	building envelope cooling load
BD	Buildings Department, the Government of the HKSAR, China
CDF	cumulative distribution function
CIBSE	Chartered Institution of Building Services Engineers
CO_2	carbon dioxide
COP	coefficient of performance
CSD	Census and Statics Department, the Government of the HKSAR, China
DA	daylight aperture
DBT	dry bulb temperature
DPT	dew point temperature
DF	daylight factor
DT	temperature difference between exterior and interior design conditions (in degrees Celsius)
ECMs	energy conservation measures

EEAC	Energy Efficiency Advisory Committee
EEO	Energy Efficiency Office
EERS	Energy Efficiency Registration Scheme
EMSD	Electrical and Mechanical Services Department, the Government of the HKSAR, China
EPD	equipment power density
ERC	externally reflected component
EUI	energy use index
FS	Finkelstein-Schafer statistics
GHG	greenhouse gas
GSR	global solar radiation
HKO	The Hong Kong Observatory, the Government of the HKSAR, China
HKSAR	The Hong Kong Special Administrative Region
H/L	ratio of height of external obstruction to separation
HVAC	heating, ventilation and air-conditioning
ICL	internal cooling load
IEU	incremental electricity use
IPCDP	incremental peak cooling plant demand
IPEU	incremental peak electricity use
IRC	internally reflected component
IWEC	international weather for energy calculations
Lm/W	lumen per Watt

LPD	light power density
LT	light transmittance
MBE	mean-bias error
NCDC	National Climatic Data Centre, US department of Commerce, Asheville, North Carolina, USA
OTTV	overall thermal transfer value
OV	projection ratio of overhangs
PB-BEC	performance-based building energy code
PELB	Planning, Environment and Land Bureau, the Government of the HKSAR, China
PER	primary energy requirement
RMSE	root-mean-square error
RVD	Rating and Valuation Department, the Government of the HKSAR, China
SC	shading coefficient
SCLF	solar cooling load factor
SF	projection ration of side fins
SHGFs	solar heat gain factors
SkyC	sky component
TJ	terajoule
TMM	typical meteorological month
TMY	typical meteorological year
TMY2	version 2 of TMY weather data set
TRY	test reference year

TWY	typical weather year
USA	The United States of America
VAV	variable-air-volume
WSP	wind speed
WWR	window-to-wall ratio
WYEC	weather year for energy calculation

Nomenclature

A_g	area of glazing (m²)
A_{tw}	total gross exterior wall area (m²) = $A_g + A_w$
A_w	area of opaque wall (m²)
DT	temperature difference between exterior and interior design conditions (°C)
E_{in}	illuminance on workplane (lux)
E_v	outdoor vertical illuminance (lux)
E_{vg}	outdoor global illuminance (lux)
FS	value of FS statistic
IC	influence coefficient
IP	partial derivates of input
IP_{BC}	base-case values of input
$\overline{IP}$	mean values of input
ΔIP	changes in input
k	rank order number 1, 2, 3, ……, n -1
K_{eff}	luminous efficacy of daylight (Lm/W)
n	total number of elements
N	number of daily readings for that month

NI	number of indices (e.g. 9 for TMY and IWEC)
OP	partial derivates of output
OP_{BC}	base-case values of output
$\overline{OP}$	mean values of output
ΔOP	changes in output
Q_g	cooling load due to glass conduction (W)
Q_s	cooling load due to glass solar heat gain (W)
Q_w	cooling load due to wall conduction (W)
Q_{gc}	heat conduction through glass windows (W)
Q_{sol}	solar radiation through glass windows (W)
Q_{wc}	heat conduction through opaque walls (W)
R^2	coefficient of determination
R_c	reflectance of internal ceiling
R_f	reflectance of internal floor
R_w	reflectance of internal wall surfaces
$S_n(x)$	value of the cumulative distribution function at x
SF	solar factor (W/m²)
T_{clg}	Cooling load temperature difference for opaque wall (°C)
T_{clw}	Cooling load temperature difference for glazing (°C)
T_{cB}	angular solar transmittance of the coated windows
T_{gB}	angular solar transmittance
T_{sol}	solar transmittance

TD_{eq}	equivalent temperature difference (°C)
U_g	U-value of glazing (W/m²°C)
U_w	U-value of opaque wall (W/m²°C)
WF_i	weighting factor for the *i*th parameter
WS	weighted sum average
$\mathrm{E_{IEUI}}$	annual energy reduction index for daylighting schemes (kWh/m^2)
$\mathrm{E_{IPEUI}}$	peak electricity reduction index for daylighting schemes (W/m^2)
$\mathrm{IEU_D}$	incremental electricity use due to daylighting (MWh)
$\mathrm{IEU}_{D,B}$	incremental electricity use of whole building due to daylighting (MWh)
$\mathrm{IEU}_{D,N}$	incremental electricity use of north perimeter zone due to daylighting (MWh)
$\mathrm{IEU}_{D,E}$	incremental electricity use of east perimeter zone due to daylighting (MWh)
$\mathrm{IEU}_{D,S}$	incremental electricity use of south perimeter zone due to daylighting (MWh)
$\mathrm{IEU}_{D,W}$	incremental electricity use of west perimeter zone due to daylighting (MWh)
IEU_{O}	incremental electricity use for non-daylighting scheme (MWh)
$\mathrm{IEU}_{O,B}$	incremental electricity use of whole building for non-daylighting scheme (MWh)
$\mathrm{IEU}_{O,N}$	incremental electricity use of north perimeter zone for non-daylighting scheme (MWh)
$\mathrm{IEU}_{O,E}$	incremental electricity use of east perimeter zone for non-daylighting scheme (MWh)
$\mathrm{IEU}_{O,S}$	incremental electricity use of south perimeter zone for non-daylighting scheme (MWh)

$IEU_{O,W}$	incremental electricity use of west perimeter zone for non-daylighting scheme (MWh)
IEU_A	the difference between IEU_O and IEU_D per building gross floor area (kWh/m^2)
$IPCPD_D$	incremental peak cooling plant demand due to daylighting (kW)
$IPCPD_O$	incremental peak cooling plant demand for non-daylighting scheme (kW)
$IPCPD_A$	incremental peak cooling plant demand per building gross floor area (W/m^2)
$IPEU_D$	incremental peak electricity use due to daylighting (kW)
$IPEU_O$	incremental peak electricity use for non-daylighting scheme (kW)
$IPEU_A$	the difference between $IPEU_O$ and $IPEU_D$ per building gross floor area (W/m^2)
$IEUI_S$	incremental electricity reduction index due to daylighting and considering shading effect (kWh/m^2)
$IEUI_{S,N}$	incremental electricity reduction index for north perimeter zone due to daylighting and considering shading effect (kWh/m^2)
$IEUI_{S,E}$	incremental electricity reduction index for east perimeter zone due to daylighting and considering shading effect (kWh/m^2)
$IEUI_{S,S}$	incremental electricity reduction index for south perimeter zone due to daylighting and considering shading effect (kWh/m^2)
$IEUI_{S,W}$	incremental electricity reduction index for west perimeter zone due to daylighting and considering shading effect (kWh/m^2)
$IEUI_{S,F}$	incremental electricity reduction index due to daylighting and considering shading effect for each floor (kWh/m^2)
$IEUI_{S,FN}$	incremental electricity reduction index due to daylighting and considering shading effect for north perimeter zone at each floor (kWh/m^2)
$IEUI_{S,FE}$	incremental electricity reduction index due to daylighting and considering shading effect for east perimeter zone at each floor (kWh/m^2)

$\mathrm{IEUI}_{S,FS}$ incremental electricity reduction index due to daylighting and considering shading effect for south perimeter zone at each floor (kWh/m^2)

$\mathrm{IEUI}_{S,FW}$ incremental electricity reduction index due to daylighting and considering shading effect for west perimeter zone at each floor (kWh/m^2)

δ_i absolute difference between long-term CDF and the yearly CDF at $x_{(i)}$ value

ϕ the angle of obstruction measured from the window sill above the horizontal of individual storeys (º)

θ angle of solar incident (º)

θ_B angle between the roof of reference and the obstructing buildings (º)

θ_N angle of obstruction at north of whole building (º)

θ_E angle of obstruction at east of whole building (º)

θ_S angle of obstruction at south of whole building (º)

θ_W angle of obstruction at west of whole building (º)

Chapter 1 Introduction

Climate change has been recognised as a serious environmental problem in the world. Changes in atmospheric concentrations of greenhouse gases (GHGs) and aerosols, land cover and solar radiation alter the energy balance of the climate system (IPCC, 2007). The increased concentrations of GHGs are a direct consequence of human activities. The global increases in carbon dioxide (CO_2) concentration are due primarily to fossil fuel use (Nawaz and Tiwari, 2006), and land use change, while those of methane and nitrous oxide are primarily due to agriculture (IPCC, 2007). Furthermore, the public are becoming aware that, if left not remedied, climate change will also lead to social and economic problems (Kılınç et al., 2008). The political leaders of many countries have realized that there is an imperative need to reduce GHG emissions on a worldwide scale.

CO_2 ranks amongst the most important anthropogenic GHGs, accounting for 82% of the total (Damtoft et al., 2008). The global increases in CO_2 concentration are due primarily to fossil fuel use, which is mainly used to produce energy. Energy-related CO_2 emissions contribute to three main end-use demand sectors: industry, buildings and transportation (De la Rue du Can and Price, 2008). Building-related GHG emissions (including direct emissions from the building sector and the emissions from electricity use) are approximately a third of global total CO_2 emissions (Price et al., 2006). Energy efficiency in buildings offers a large link between sustainable development and GHG mitigation (Levine et al., 2007).

In Hong Kong, all the energy consumed has to be imported and most of the imported energy is consumed for power generation (Chow, 2001b). The commercial sector accounts for a large share of total energy use. This is especially true of the central air-conditioned buildings located in the hot and humid subtropical area (Chan, 2003). The increase in oil prices since 2002 has depressed the current account balance for net oil importing economies like Hong Kong. Therefore, high oil prices become an adverse impact on sustainable development and prosperity. For this reason, energy conservation in the majority of commercial buildings has become a valuable and developmental strategy of energy polices of the government. In general, air-conditioning and electric lighting are the two major consuming items in buildings. Daylighting is one of the solutions to reduce the environmental impact on the climate and reduce energy use in buildings (Lau, 2005). A significant amount of the cooling load comes from solar radiation; electric lighting load can also be reduced by using daylight. Because of the sustainability of daylight, there is a potential for reducing lighting energy use by using this non-carbon-based source. Therefore, proper daylighting design is considered one of the most effective ways of abating the demand for energy and adverse effects on the environment, and even for improving the qualities of visual comfort and health (Gupta and Tiwari, 2004).

Opportunities for daylighting are strongly influenced by architectural decisions at the early design stage, such as building form, the provisions of skylights and size, material, shape and position of windows (Levine et al., 2007). The other challenge is the application of effective daylighting strategies for retrofitting existing buildings due to lack of design flexibility. Studies enabling a better understanding of daylighting and its energy performances in various architectural designs and daylight availability in the developed urban built environment are therefore of great value to the development of sustainable building. This chapter presents the background and objectives of the research study and the structure of this thesis.

1.1 Background

Hong Kong is famous for its high-rise building blocks on both sides of Victoria Harbour. The density and quantity of these buildings are at the same international level as in most major cities worldwide. As the economy of Hong Kong grew very rapidly since the 1960s, people's living standard has improved and the demand for energy has increased sharply over the past decades (Chow, 2001a). Figure 1.1 shows the total primary energy requirement (PER) during the 26-year period from 1979 to 2004 (CSD, 1979-2004a). It can be seen that the primary energy requirement increased from 195,405 terajoules (TJ) in 1979 to 575,974 terajoules (TJ) in 2004, representing an average annual growth rate of 4.4%. The decline in PER between 1994 and 1997 was due mainly to the reduction in the sale of electricity to mainland China and importation of nuclear power starting from 1994. A steep rise of PER was observed from 1998 to 2000 showing that an influx of energy was suddenly required to overcome the global event of protecting computer operation due to Y2K chronological problems in the computer industry, during which testing and recalibration of all computers were at their peak, resulting in more energy consumption (Chan, 2003). In 2004, over half (nearly 60%) of the total PER was used for the generation of electrical power (CSD, 1979-2004a). The rest of the PER was shared between gas supply for cooking, hot water and some industrial applications and petroleum product transport, etc (EMSD, 2007a).

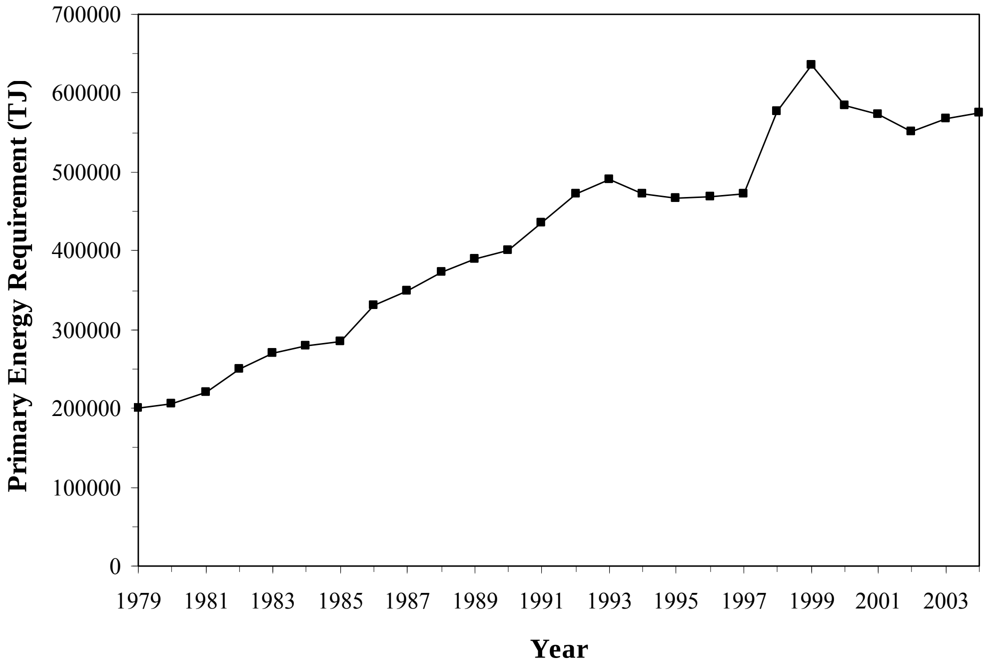


Figure 1.1 Total Primary Energy Requirements (PER) from 1979 to 2004

To further break down the electricity consumption, there are four major end-users, namely industrial, commercial, residential and export of power to mainland China. Figure 1.2 shows the graphical breakdown of these four sectors (CSD, 1979-2004b). It is found that there has been a substantial increase in all sectors except industry. During the 1980s, the local economy shifted from being manufacturing-based to services-oriented operations. Many commercial buildings had been built by property developers under the commercial services economy. For this reason, the commercial sector overtook the industrial sector to become the largest electricity end-user. In 2004, building stock, both commercial and residential, accounted for 83% of the total electricity power consumption, representing half of the total PER in Hong Kong.

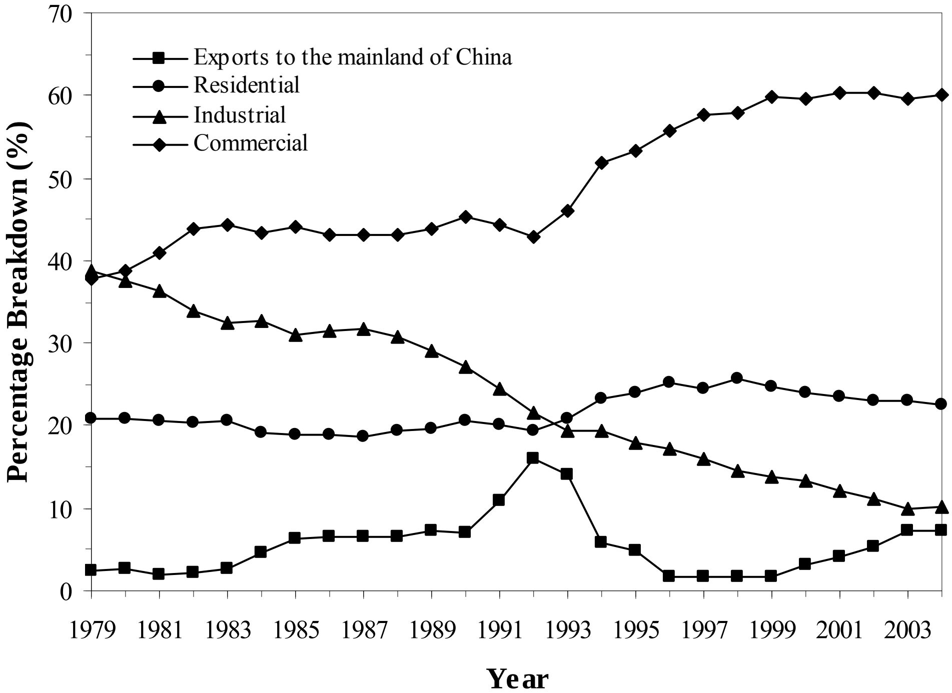


Figure 1.2 Breakdown of Electricity PER in the Economic Sectors

To get some idea of the actual electricity consumption situation in the residential and commercial sectors, energy data was gathered and analysed. Figure 1.3 shows the electricity consumption in the commercial and residential sectors during the 26-year period (1979-2004). In general, the electricity use in both the commercial and the residential sectors has been increasing unabated, even during the economic downtown in the late 1990s. Electricity use in the commercial and residential sector rose by 7.9 and 6.2% respectively per year during the 26-year period. Most of the electricity consumption is for the thermal comfort of the indoor built environment. In subtropical Hong Kong, a large proportion of energy use is for air-conditioning during the hot, humid summer months. The consumption is the energy actually delivered to and used in buildings for the purpose of controlling the environment and meeting the basic needs of the occupants. The energy used in manufacturing and distributing the materials during construction of buildings (i.e. the embodied energy) is additional to the direct energy use and could account for a significant proportion of global energy consumption (Alcorn and Baird, 1996; Ayres et al., 1998). Buildings, therefore, play an important part in any comparative study of energy end-users and overall energy efficiency strategy.

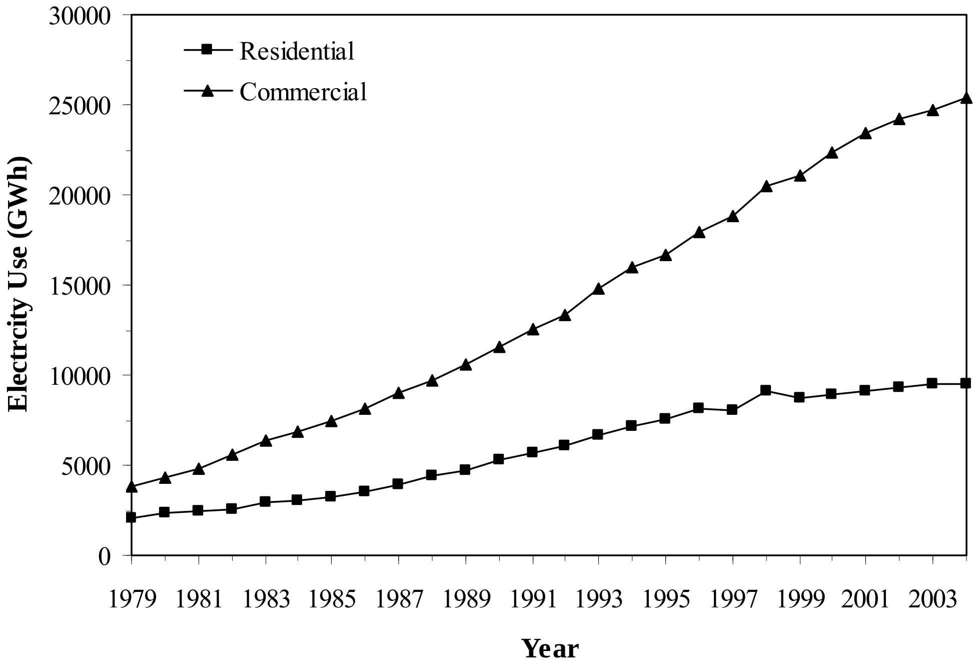


Figure 1.3 Electricity Consumption in the Commercial and Residential Sectors

The government of Hong Kong has a basic economic policy in that it will not impose any unnecessary restrictions on and cause any interference to the business sector. The economic operation of Hong Kong is basically market-driven and the government only intervenes when there is mal-practice or other abnormal social phenomena/considerations. Over the past decades, this fundamental policy has shaped the development of Hong Kong's energy sector, such that the private sector can supply energy in whatever forms to suit the market needs.

With regard to energy activities, Lam (1998) pointed out that the 1990s were a period of fundamental change in policy instruments and agency responsibilities. Building stocks account for a significant proportion of the total primary energy consumed - this should be one of the major areas for promoting greater energy efficiency. In 1991, the Hong Kong government set up an Energy Efficiency Advisory Committee (EEAC) to deal with energy efficiency issues. The committee was under the sponsorship of the Planning, Environment and Land Bureau (PELB). Energy efficiency and conservation in buildings (both new designs and existing) were the key areas addressed in the working group. To better coordinate and implement energy efficiency in general and energy conservation in buildings in particular, the Energy Efficiency Office (EEO) was established within the Electrical and Mechanical Services Department (EMSD) in 1994. In recognition of the importance of energy matters, the Energy Advisory Committee was set up in 1996 by the Economic Services Bureau to advise the government on energy issues and sustainable developments in Hong Kong. The EEO has initiated a number of energy efficiency measures and programmes, details of which can be found in their biannual publications, Energy Wits, or website: www.emsd.gov.hk/emsd/. Lai (2003) estimated that a saving of around 360GWh of electricity was achieved through these measures and programmes in 2002. This figure is equivalent to a saving of HK$330 million in energy costs and a reduction in greenhouse emissions of 0.26 million tonnes of carbon dioxide.

The EEO of the HKSAR government is very active in the development of building energy standards and codes to encourage more energy-efficient designs of buildings and building services installations. Besides the overall thermal transfer value (OTTV) standard, the other published codes are currently being implemented on a voluntary basis under the Hong Kong Energy Efficiency Registration Scheme (EERS) for Buildings launched in 1998. The EMSD did not think it satisfactory that 791 buildings had been registered under the scheme and only 24% were private premises (EMSD, 2007b). Therefore, the government is proposing to turn the voluntary building energy codes into statutory requirements by 2010. Building energy conservation is a major energy policy in Hong Kong.

In subtropical Hong Kong, commercial and residential buildings are the major electricity consumers. The earlier works by Lam and Chan (1994, 1995) on energy audits and surveys of commercial buildings showed that heating, ventilation and air-conditioning (HVAC) account for 50-60% of the total electricity consumption in fully air-conditioned commercial buildings. Lighting is the second largest electricity-consuming item, which accounts for 20-30%. Similar patterns have been observed for the residential sector, in which air-conditioning and electric lighting account for 33 and 10% of total household electricity use, respectively (Lam, 1996). As for commercial venues, such as offices and shopping centres, they tend to have a longer cooling season from mid-March to November mainly due to the higher envelope heat gains. More energy efficient designs and effective operation and maintenance of these buildings may reduce the demand for air-conditioning and lighting and hence lower the energy use. Generally speaking, the cooling requirements of buildings are regulated by building envelope design. However, it is not flexible enough and is restricted by the OTTV requirement in Hong Kong. Moreover, some luxury lighting fixtures may not comply with the building energy codes. Therefore, in 2001, a performance-based building energy approach was introduced to offer a choice to building designers and engineers who wish to pursue and adopt innovative building design.

It is envisaged that there is scope for integrating daylight with electric light to save building energy use. Electricity consumption for lighting is substantial in commercial buildings. Moreover, the heat dissipation from the artificial lighting is a major contributor to cooling load. Daylighting is recognised as an important and useful strategy in terms of energy-efficient building design. Natural light is free and its high efficacy provides the same illuminance level with less amount of heat generated. An understanding of daylight availability and the energy implications in commercial buildings is definitely useful for daylighting design. An efficient daylighting design is not only to provide illuminance levels sufficient for good visual performance but also to maintain a comfortable and pleasing atmosphere. Glare, or excessive brightness contrast within the field of view, is one aspect of lighting that can cause discomfort to the occupants of a space (Ander, 2003). However, there still seems to be a strong human preference for being close to a window, and for buildings that are well daylit (Baker and Steemers, 2002). In Hong Kong, there is little information about daylighting and its energy performances for the whole commercial development. It shows that there is need to develop some simple design methods for evaluation of daylighting performances in buildings.

Based on the measured data, daylight potential can be investigated and useful information about daylighting systems can be obtained. Building energy characteristics with daylighting controls are at present not well defined because the parameters involved are complex, diverse and insubstantial in nature. To tackle this difficulty, detailed analysis of cooling loads, lighting energy and estimation of building energy reduction, particularly using daylighting designs, can be achieved by computer simulations. Transmitted daylight into buildings is affected by building façade design. To achieve a better daylighting design, energy implications with different OTTV designs and daylighting schemes should be established.

As a highly developed financial centre in the world, there are many high-rise buildings built in a small business district. Therefore, shading effect should be seriously considered in daylighting design. This could result in overestimation of daylight potential and cooling requirements at the lower floors. By using computer simulations, the building energy performance due to the shading effects from external obstructions can be estimated. The energy impacts on four perimeter zones (North, East, South and West) of individual floors can also determined. Furthermore, overall energy reduction equations due to various daylighting designs including considerations of building envelope design and external environment can also be developed to provide information during the initial design stage.

Daylighting schemes can also be applied to existing buildings undergoing major renovations. Due to limitation of design flexibility on the building envelope, advanced solar control films can be introduced to reduce the penetration of solar radiation into buildings. In consideration of these two designs, energy performance (i.e. annual energy consumption and particularly in cooling requirements) should be significantly reduced for existing buildings. The research work includes data measurement and validation, energy prediction models development for new buildings and energy saving potential for existing buildings with an emphasis on daylighting schemes.

1.2 Objectives

The purpose of the research in this thesis is to establish systematic methods for the assessment and evaluation of daylighting and energy performance of central air-conditioned office buildings and other types of commercial building with similar lighting design in Hong Kong. It is hoped that the study can provide architects and building engineers some reliable design tools to estimate the energy savings due to various daylighting designs and draw useful information for achieving optimum energy efficiency in building design and operation. The objectives are as follows:

(i) To study the weather files for building energy analysis and to establish a typical weather year for daylighting and building energy simulations in Hong Kong.

(ii) To develop computer simulation models for the analysis of the energy performance of central air-conditioned buildings and to investigate the interactions between daylight design parameters and energy uses.

(iii) To analyse shading effects at the individual floors of buildings due to different configurations and directions of external obstructions.

(iv) To establish a new energy conservation scheme (daylighting control and solar control film) for existing buildings and estimate the likely cooling load and lighting energy reductions and the corresponding energy savings.

1.3 Outline of Original Contribution and Thesis Structure

The original contribution to knowledge from this study can be summarised as follows:

(i) A representative weather database is developed for Hong Kong. This weather database is not only used to perform building energy simulation but also assists in daylight analysis in Hong Kong.

(ii) By using advanced computer simulation techniques, energy implications on artificial lighting and air-conditioning systems due to various daylighting design schemes (envelope designs and external obstructions) can be determined for a whole building block.

(iii) Energy equations and some simple design models for prediction of energy saving potential of daylighting are also developed and validated. Designers can use these tools to evaluate overall building energy performance when considering daylighting at the conceptual design stage.

(iv) Besides new building development, daylight availability and energy implications are also examined for existing buildings in densely built environments. This enables more daylighting designs to be incorporated for building retrofits in Hong Kong.

This thesis consists of eight chapters. The subject matter of each chapter is outlined as follows:

Chapter 2 highlights the features and importance of building energy codes and investigates their developments in Hong Kong. The newly implemented performance-based building energy approach is studied and discussed. Daylight availability and key factors affecting daylighting are addressed for Hong Kong. A computer simulation approach is proposed to assess building energy performance for daylighting schemes.

Chapter 3 focuses on the development of input files (i.e. reference buildings, outdoor design conditions and weather database) for performing energy analysis on daylighting design. A base-case office building including building envelope design and system design is established via a detailed simulation program, namely EnergyPlus. A representative weather database is determined and weather files for building energy simulation are developed.

Chapter 4 reports on an investigation of the measured electric lighting and cooling energy in an office before and after installing a daylight-linked dimming system. The energy saving potential is evaluated by computer simulation techniques. Sensitivity analysis is carried out to examine the important design parameters of daylighting.

Chapter 5 studies building envelope designs and OTTV implications in daylight and energy analysis. Some simple design graphs are established to determine annual electricity and peak loads (electricity demand and cooling plant capacity) reductions with different envelope designs and daylighting schemes.

Chapter 6 investigates building energy performance due to shading effects from nearby buildings at different orientations. The energy impacts of external obstructions on individual floors are also discussed. In addition, multiple regression analysis is performed to generate and analyse overall energy equations for daylighting schemes when considering internal and external design elements together.

Chapter 7 develops correlation models to predict the solar and light transmittance for coated glazing based on angle of solar incident and measured transmitted solar and illuminance. This chapter also presents the daylighting performance and energy issues for existing office buildings with different envelope designs when considering solar film coatings and high frequency dimming controls in retrofits.

Chapter 8 summarizes the major findings of the research work, states the limitations of the study, and recommends future research work to enhance building energy prediction for daylighting design.

Chapter 2 Building Energy Performance via Computer Simulation Approach

2.1 General

Hong Kong has no energy resources of her own and most imported fossil fuels are used for electricity generation. There are many immediate environmental adverse effects including poor air quality and polluted skies that arise from the burning of fossils fuels to generate energy (Reddy and Shekar, 2007). Electricity is high grade energy and in general three units of primary energy inputs are needed to produce one unit of electricity output, with the other two units being wasted as heat. This indicates that one unit of electricity saved means about three units of non-renewable fossil fuel are saved together with likely pollutant reductions. Commercial buildings consume the biggest portion of electricity use in Hong Kong. The potential for electricity savings is probably the greatest in the commercial sector where a significant portion of the energy demand is expended by HVAC systems and artificial lighting (Li et al., 2002a). Hence, proper building and services design can contribute to smaller HVAC plant and lower the peak power demand and annual energy consumption of buildings.

As a measure to improve the effectiveness of using energy in buildings, the Hong Kong Government has issued five energy codes, namely the OTTV code (BD, 1995), the lighting code (EMSD, 1998a), the air-conditioning code (EMSD, 1998b), the electrical code (EMSD, 1999) and the lift and escalator code (EMSD, 2000). Buildings must achieve at least a minimum standard of energy efficiency when fulfilling the basic requirements for building and systems designs in the energy codes. However, the codes are prescriptive criteria, which give less design flexibility for buildings. In 2003, performance-based building energy code (PB-BEC) based on the total energy budget approach was issued to provide an alternative compliance route to the five codes. Since the ultimate goal of the PB-BEC is to reduce energy use in buildings, trade-offs among the energy performance of various components of the building and the services systems are allowed (Yik et al., 2002). This implies that non-compliance in one component, which is difficult to rectify, could be compensated by enhancing the energy performance of other components.

The PB-BEC states that useful energy generated from renewable energy sources or recovered from suitable sources can be considered in the evaluation of building energy performance. Utilisation of daylight controls is particularly one of the energy savers proposed in the guidelines of the code (EMSD, 2005). Many researchers have revealed that daylight-linked lighting controls provide significant energy saving by 30 – 60% in office buildings (Tetri, 2002; Onaygil and Guler, 2003; Franzetti et al., 2004; Galasiu et al., 2004; Roisin et al., 2008). In subtropical Hong Kong, lighting energy expenditure could be reduced by 33 – 40% under dimming controls (To et al., 2003; Li et al., 2006). Energy savings resulting from daylighting mean not only low electric lighting and reduced electrical demands, but also reduced cooling requirements. Daylight, however, is always accompanied by solar heat gain. An increase in the OTTV and hence cooling requirement due to a bigger glazing area can be compensated from the daylight-induced energy savings (Li et al., 2002a;

2005). This means that building envelope and system designs can be more flexible if proper daylighting control is employed.

In Hong Kong, the building regulations prescribe a minimum distance between building blocks based on the concept of sustained vertical angle requirements (currently 71.5°) and a minimum glazing to floor ratio of 10% for all habitable spaces for natural lighting design (HKSAR, 2000). However, the indoor visual environment is commonly provided by artificial lighting in commercial buildings. There is room for consideration of giving daylighting credits in the OTTV standard. Daylighting performance in buildings is affected by many factors including orientation, window area, glass type, shading and external obstructions (Li, et al., 1999). The performance-based approach provides an effective platform for performing energy analysis on various daylighting designs for commercial buildings. The simulation approach offers great capability for determining a wide range of design features and daylighting implications (Tsou et al., 2003). Very often, building energy simulation tools are used for analysing the energy consumption in buildings so as to establish the basis for the building energy codes and their energy requirements (Hui, 2003). This chapter discusses energy requirements for building designs, daylight availability for office buildings and introduces the approach to building energy performance using computer simulation techniques.

2.2 Development of Building Energy Standards in Hong Kong

The first building regulation on energy efficiency came into operation in July 1995. This regulation enforces statutory control on the design of the building envelope of new commercial and hotel buildings by using the overall OTTV method (BD, 1995). It can help raise concern and awareness of building energy conservation, promote energy-efficient designs and form a basis for assessing energy performance for building development (Lam and Hui, 1996b). Some Southeast Asian Nations (ASEAN) countries have also used this method to launch the prescriptive requirements to suit their country climates. Singapore was the first nation to develop an OTTV standard which was implemented in 1979 for commercial buildings (BCD, 1979). The other four ASEAN countries, Indonesia (Janda and Busch, 1994), Malaysia (MOE, 1989), the Philippines (Department of Energy, 1993) and Thailand (Chirarattananon, 1992), used Singapore's development as a reference model to develop their own OTTV requirements. It is believed that the OTTV approach is a simple method suitable for countries with hot climates which have just started to launch energy standards to assist building energy conservation designs.

The OTTV method deals with conduction heat gain through the building envelope as well as solar heat gain through the windows. This concept generally applies to hot and humid climatic areas, where air-conditioning is the major energy consumer. In general, the OTTV method is easy to understand and implement and designers are willing to use this value as a design guideline. However, the OTTV method is prescriptive in nature; architects and engineers have less freedom in the design of the building envelope and the selection of building materials. Moreover, the biggest limitation of the OTTV method is that it only deals with the building envelope and does not consider the coordination of building services systems (such as lighting and air-conditioning) to optimise the combined energy performance (Hui, 1997). Therefore, the use of OTTV as the only control parameter is unfair and cannot ensure that building energy is really used efficiently.

Apart from the mandatory OTTV code, the other four building services systems codes are voluntary in nature. To assist building services design, supplementary guidelines for lighting and air-conditioning installations have also been published as explanatory notes to these energy codes. To encourage the use of energy-efficient equipment in building development, the Hong Kong Government is going to consult the public as to whether they should be made mandatory by 2010. With the implementation of the mandatory scheme for these four codes, additional electricity savings of 2.8 billion kWh will be achieved in the first decade of implementation, equivalent to a reduction of 1.96 million tonnes of CO_2 emission (EMSD, 2007b).

2.2.1 Prescriptive Codes

The local OTTV standard on building envelope design and the four building energy codes on building services installations are prescriptive (i.e. they specify the design parameters in terms of energy performance and the minimum design requirements). The rationale for taking the prescriptive approach in the 1990s was that there had never been any building energy efficiency regulations before in Hong

Kong. In addition, the prescriptive methods are simple, easy to follow and most important of all, have a good chance of being accepted by the stakeholders, especially the building profession. The OTTV standard is employed to control the heat gain from the outside to the indoor environment through the external envelope of a building. The smaller the OTTV, the less will be the energy use for cooling. The weakness is less flexibility in building envelope design and choices of construction method and glazed window materials so as to comply with the prescribed OTTV. The other four codes provide the basic requirements on selection of energy-efficient building services equipment for building developments.

Table 2.1 summarizes the building and premises types covered by the OTTV and the four prescriptive building energy codes. It can be seen that all five codes provide the basic requirements and prescriptive energy performance of electrical and mechanical equipment for new commercial buildings, hotels and commercial portions of residential developments that are designed with central air-conditioning systems. After reviewing the control items in the four prescriptive building energy codes for building services installations, it can be found that most of them are related to the efficiency of installed power of the electrical and mechanical equipment (i.e. coefficient of performance (COP) of water chillers, limits on fan power demand per unit design flow rate, luminous efficacy of lamps, control gear loss of lighting fixtures, minimum motor efficiency, etc.). The OTTV code is also related to the annual cooling energy consumption and the peak cooling load of the air-conditioning systems in commercial buildings. This implies that the building services equipment can be selected based on the information provided by those energy codes. Therefore, a low energy office building can be developed based on its compliance with the prescriptive requirements.

TABLE 2.1 Summary of the types of buildings covered by the building energy codes

Energy Codes	Coverage of building types and areas	Exceptions
Air-conditioning	All buildings provided with air conditioning installations	Domestic buildings; medical buildings; industrial buildings; and any are and any part of the buildings to be used for domestic, medical or industrial purposes.
Electrical	All fixed electrical installations for all buildings	Emergency systems; buildings with a total installed capacity of 100A or less; buildings used solely for public utility services; buildings designed for special industrial process may be partly or wholly exempted; and Equipment owned by the public utility companies.
Lift & Escalator	Passenger lifts, freight lifts, lifts used for vertical transportation of motor vehicles, bed passenger lifts, escalators and passenger conveyors in all buildings	Builders' lifts and hoists used in a building construction site; services lifts; lifts and hoists installed in a performance stage; lifts equipment for building maintenance; and traction lift equipment with load > 5000kg and rated speed > 3m/s.
Lighting	Offices, schools, car parks, places of public entertainment & recreation, places of public assembly, hotels, shops, department stores, restaurants, and communal areas of residential buildings	Indoor spaces of a hospital, a clinic or an infirmary; spaces used for utility services; spaces for domestic inhabitation or industrial processing; specialized lighting installations solely used for industrial research application, television broadcasting, theatrical production and audio-visual presentation; display lighting for exhibit or monument; and emergency lighting of non-maintained type.
OTTV	New commercial and hotel buildings	Other than new commercial and hotel buildings.

2.2.2 Performance-Based Energy Code

In view of the lack of design flexibility of the prescriptive approach, the Hong Kong government commissioned a consultancy study on a PB-BEC in 2001. Full consultation with all stakeholders took place in 2003 after the completion of the study. The objectives of this code are to facilitate efficient use of energy in buildings and to promote innovative approaches to achieve optimum building energy performance (EMSD, 2003). The building energy performance assessment method stated in the PB-BEC is based on the total energy budget approach, which was first launched in ASHRAE Standard 90.1-1989 (ASHRAE, 1989). This flexible approach can cater for different aspects of building designs as long as the total design energy does not exceed the allowed energy budget. Like the prescriptive energy codes on building services installations, the PB-BEC should be voluntary during the initial years with the ultimate aim of making it mandatory later. The success of such alternative building energy codes will rely on the determination of the authorities to persist with the policy, the backup of research and development and the cooperation of the building professionals who are willing to accept the initial inconvenience.

The new energy performance assessment framework is illustrated in Figure 2.1. It provides an alternative way for demonstrating compliance by the performance approach, which provides flexibilities in making trade-offs among the performances of different envelope designs and building services systems. Compliance with this code is measured by calculating the annual energy consumption for the designed building and comparing it against the energy use of a commensurate reference building, both of which are estimated by computer simulation. The designed building should be developed by modifying the description of the reference building. The designed building should have all the features of the reference building, but it should be modified to meet the exact requirements of the OTTV and the four prescriptive building energy codes (e.g. HVAC system load design and luminous efficacy of the lighting system). Compliance with the PB-BEC will be achieved if the predicted annual energy consumption of the designed building does not exceed the total energy budget. It also allows certain systems to exceed the minimum requirements on the condition that the energy performance for other systems in the building is improved to compensate for the non-compliance of the specific systems. This alternative approach applies for designing of new commercial buildings and hotels and does not apply to any area and any part of a building to be used for domestic, medical or industrial purposes in Hong Kong.

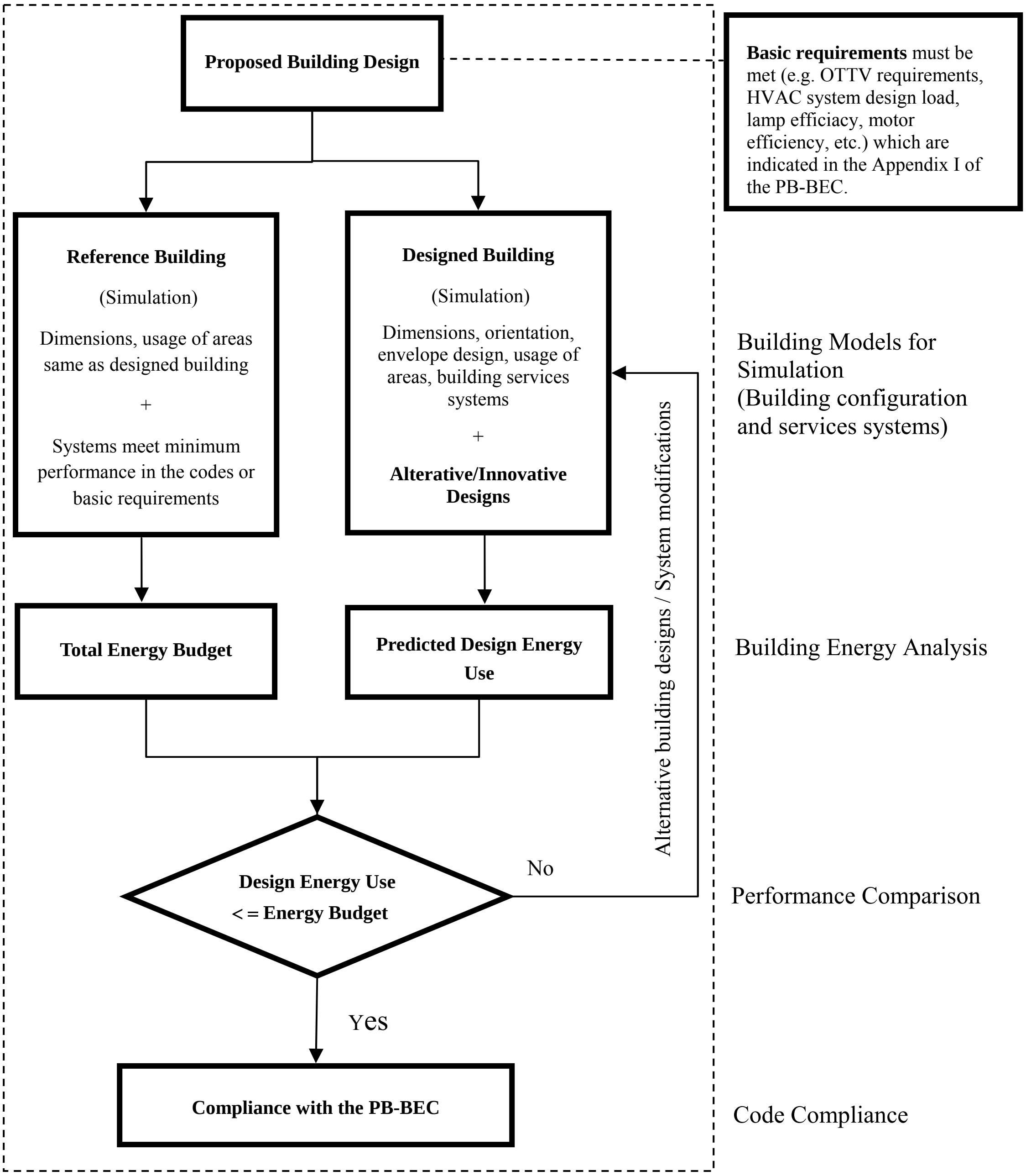


Figure 2.1 Framework of assessment method of a PB-BEC

2.2.3 Other Considerations

There are pros and cons on both prescriptive and performance-based methods when pursuing new design of new buildings or renovating existing ones. The righteousness and mindset of choosing either one of these building energy codes or standards to suit the building project will involve four issues. Firstly, classification by building type is important because different types of buildings, such as offices, shopping malls, hospitals, hotels, etc, have their own design features and parameters. The operation and occupancy schedules, equipment heat loads, application of different climatic control systems and lighting features to suit the operational needs, will also affect the building energy consumption characteristics. In such cases, the performance-based building energy approach will definitely be better than the prescriptive one. Secondly, to achieve flexibility of the performance-based energy standards or codes, the compliance methodology should be tailor-made to suit the local situation as well as different stages of the development of the energy codes. It might include different paths to demonstrate compliance, such as the descriptive path, system performance path and the energy cost budget. To suit different users, the building energy codes may also include both prescriptive and performance options as well as the alternative compliance paths. Thirdly, the implementation and enforcement issues are discussed in society. If the building energy codes are going to be mandatory, the procedure must be well defined and clear for checking and implementation. Nevertheless, this may not be that simple because of the complexity involved with the particular building and building services design and the operation and occupancy scheduled details. Whether the prescriptive or performance-based method, the most important factor is the acceptance of the policy as a whole by the public and the building profession. Finally, the local information on building energy efficiency is required in order to formulate the specific requirements and to justify the methods being adopted. The development of building energy standards involves two main processes, namely policy and analysis. The policy process is the task of the government. For the analysis aspect, there are three basic requirements to support the development of the building energy codes in the analysis process. They are the development and analysis of the local weather data. Hui (1996) reported thoroughly on the rationale and computational details of the local weather data files, the analysis and establishment of the database of the typical building types, and the development of the building energy simulation techniques and analysis (Chan, 2003). The analytical techniques will demonstrate an accurate total building budget for comparative study of energy conservation schemes.

2.3 Daylighting Design for Cooling-Dominated Buildings

In subtropical Hong Kong, most of the electricity consumed in commercial buildings is used for creating a thermally and visually comfortable built-environment through air-conditioning and artificial lighting. Recent work on the electricity end-use load characteristics of air-conditioned office buildings has revealed that air-conditioning and electric lighting account for about, respectively, 50% and 25% of total building electrical demand (Lam et al., 2004). With such high percentage electricity expenditure, it is believed that lighting and air-conditioning are the two key areas for making the most substantial energy savings in commercial buildings. In this regard, there has been an increasing interest in incorporating daylight in architectural and building designs to reduce lighting and cooling energy use in buildings.

However, surveys of current architectural designs and construction practices for some existing commercial buildings in the private (Lam and Goodsall, 1994) and public (Chan, 2003) sectors have indicated that only a few buildings incorporate any daylighting scheme. Discussions with local architects and building designers have revealed that one of the reasons for the unenthusiastic response to daylighting design schemes is the absence of some simple methods or guidelines, which would enable the designers to easily assess the likely energy savings from daylighting and the corresponding increase in solar heat gain through fenestration. To perform an analysis of daylight availability in office buildings, the key factors affecting daylighting performance have to be addressed.

2.3.1 Solar Radiation and Outdoor Illuminance

Energy-efficient daylighting designs often require the estimation of direct and diffuse radiation and outdoor illuminance on a horizontal plane and vertical surfaces. Horizontal solar data can be used in studying horizontal fenestration such as skylights. Nevertheless, there are greater demands for knowledge of solar radiation and daylight level on vertical surfaces, particularly for high-rise office buildings. Lam and Li (1996a) revealed that horizontal solar radiation tends to be more evenly distributed in summer and over 80% of measured data occurs during office hours 9:00-17:00 and, indicates the significance of solar heat gain in air-conditioned offices in Hong Kong. It has been reported that solar heat gain accounts for over half of the total building envelope cooling load (Li et al., 2003). Higher solar heat gain, however, could also mean more daylight available for a daylighting scheme. Chung (2003) reported that the external horizontal illuminance exceeds 10 klux for over 80% of normal office hours in a year in Hong Kong. Muneer et al. (2000) also indicated that yearly horizontal illuminance of Hong Kong is always higher than some western cities, i.e. Nantes, Lyon, Lisbon, Albany and Bracknell. These reveal that daylighting designs can be applicable on building development in Hong Kong. For energy-efficient building designs, accurately knowing the amount of solar radiation and daylight level on vertical surfaces is also important, particularly for high-rise buildings. Li and Lam (2000a) analysed the vertical daylight illuminance for Hong Kong from 1996 to 1998. They indicated that over 60% of the time indoor illuminance of perimeter zones of office and domestic buildings can be provided by natural light if the required external vertical illuminance is 10klux. Therefore, it can be concluded that the potential of utilizing daylight to reduce electricity use and the associated sensible cooling load due to artificial lighting is high for local building development.

For building energy analysis, the commonest method of estimating daylight investigated by researchers has been the derivation of illuminance values from solar radiation using the luminous efficacy approach (Gillette and Treado, 1985; Littlefair, 1985 and 1988). The luminous efficacy approach is perhaps the most versatile and easily applied way to calculate outdoor illuminance. The luminous efficacy of daylight, K_{eff}, is defined as the ratio of daylight illuminance to solar irradiance and uses the unit of lumen per Watt (lm/W). Luminous efficacy is a convenient quantity in the calculation of daylight availability and lighting energy use in buildings and, in principle allows for most of the climate and latitude-related variations. It enables daylight data to be generated from the more widely measured solar radiation data for places where measured outdoor illuminance data is not available. Lam and Li (1996b) found that the global luminous efficacy on a horizontal plane ranges from 80 to 150lm/W for most of the year in Hong Kong. In terms of energy efficiency, this is much better than the 30-90lm/W for fluorescent lamps commonly installed in office buildings (Chan and Yeung, 2005), because less heat is introduced to achieve the same lighting level and less cooling demand will be required. This is particularly beneficial for places with subtropical climates like Hong Kong, where air-conditioning systems contribute to the largest part of total electricity consumption in buildings during the hot and humid summer months. Li and Lam (2000b) reported that the diffuse component predominates luminous efficacy between 105 and 140lm/W, which is considered more energy-efficient in daylighting design because of higher luminous efficacy. Furthermore, in general daylight designs, the use of direct sunlight for providing daylight in buildings has often been excluded. Problems of glare, excessive brightness ratios and thermal discomfort have supported the exclusion. Therefore, for daylighting applications, diffuse illuminance is more important and widely used. As the Hong Kong sky conditions have been described as mainly cloudy to partly cloudy, it is believed that utilisation of daylight in building designs can result in high energy savings and provide a more visually attractive environment.

2.3.2 Building Envelope Design

Solar heat gain via fenestration, contributes to a significant proportion of the building envelope cooling load. More solar radiation means more solar heat gain and, hence, more cooling load and larger air-conditioning plant (Li and Lam, 2000c). In tropical and subtropical regions, the principal objectives of fenestration design include eliminating direct sunlight and reducing cooling energy (Edmonds and Greenup, 2002). Passive solar design and daylighting, which use natural light in order to reduce electric lighting energy use, have long been recognized as potential energy-efficient design strategies for buildings (Lam et al., 2000; Galasiu et al., 2004). Daylight is considered the best source of light for good colour rendering and its quality is the one light source that most closely matches human visual response. People desire good natural lighting in their working environments (Escuyer and Fontoynont, 2001). In Hong Kong, window designs are mainly to minimize solar radiant heat gain and meet the current code of practice for the OTTV standard. Daylighting is an effective approach to allow architectural design and construction practice to have a more flexible building façade design strategy, and to enhance a more energy-efficient and greener building development. However, no daylighting credits are given to the OTTV calculations.

Evaluating daylight performance and its energy implications for office buildings, and critical design parameters affecting daylighting schemes have to be analysed at the early design stage. Study of the parameters affecting energy and daylighting performance of office buildings is essential for a more systematic and comprehensive building design scheme. With the advancement of computer technology for detailed building energy simulations, these important parameters can be examined extensively. However, very little work on parametric studies relating to daylighting designs has been done. Building envelope design parameters such as orientation of facades, window area, glass type, external shading devices indicated in the OTTV code, even photometric features on daylighting design such as internal surface reflectance (Thanachareonkit et al., 2005) were chosen for daylight analysis.

Due to the sun path in Hong Kong, south-facing façades receive certain amounts of direct sunlight in winter and mainly a diffuse component (skylight) in summer, resulting in less visual and thermal discomfort. In a side-lit room, daylight may be more nearly proportional to the external vertical daylight illuminance level. In Hong Kong, it has been found that there is a strong orientation effect on outdoor illuminance (Li and Lam, 2000b). Rooms facing south and south-east tend to receive large amounts of natural light and thus are more beneficial to daylighting designs (Li et al., 1999).

Glazing system controls the amount of daylight and solar heat gain penetrating into an interior in terms of light transmittance (LT) and shading coefficient (SC), respectively. In Hong Kong, most buildings use single glazing with an SC of between 0.3 and 0.7. It implies that reflective and tinted glass is commonly used (Chan and Chow, 1998). Recent studies indicated that there is an increasing trend for studying the applicability of advance glazing systems (i.e. switchable glazing, low-e glass, photovoltaic ventilated window, etc.) for buildings in Hong Kong (Yik and Bojic, 2006; Bojic and Yik, 2007; Chow et al., 2007). For a given glass type, the critical factor determining the transmitted daylight availability and solar heat gain is the window area. For building envelope designs, window area is commonly represented by the window-to-wall ratio (WWR) which is defined as the ratio of the total area of windows to the overall gross external wall area (including windows). Large WWR contributes to more solar heat gain, but also means increased daylight availability in buildings.

Shading devices shade the window from direct sun penetration but allow diffuse daylight to be admitted. They can be designed to reach different achievements, such as to prevent overheating, to reduce cooling loads, to control the visual environment (i.e. glare, colour, light, contrast, view towards and from the exterior), to protect the openings from atmospheric agents, to provide a "sculptured skin" of buildings (Guglermetti and Bisegna, 2006). Exterior shading devices, overhangs and side-fins, can be frequently found in medium sized office buildings in Hong Kong (Chan, 2003). They also act as control parameters in the OTTV standard. It is believed that optimum design of external shading devices can be achieved in terms of visual and energy performances.

2.3.3 Shading and External Obstruction

Shading devices shade the window from direct sun penetration but allow diffuse daylight to be admitted. Exterior shading devices frequently found in Hong Kong for office buildings include overhangs and side-fins which are more effective to block the direct sunlight and solar heat than internal shading devices such as venetian blinds and curtain blinds (Li and Tsang, 2008). During the 60s to mid-80s, buildings tended to have overhangs and side-fins with clear glass. Between the late 80s and 90s, external shading devices were not popular because more large scale prestigious building projects in up-market commercial districts had a tendency to use curtain walling. Since the late 90s, resurgent shading devices have been found and such a design has become popular again in recent years. A plausible explanation is the installation of overhangs for new buildings to meet the current Hong Kong OTTV code.

The loss of daylight, sunlight and solar gain due to obstructions is an important feature of the city (Littlefair, 2001a). Tall buildings and other obstructions are located next to each other that affect the distribution of daylight in a building as well as reducing the total amount of solar radiation received. Being one of the fastest paced commercial cities in the world, Hong Kong is characterized by high-rise office building stocks. Most of the building blocks are 20 to 40 storeys high located in various business districts (Lam, 2000). Such developments, however, may result in quite a large degree of shading effect from nearby buildings. In subtropical regions, solar heat through fenestration on vertical surfaces plays a major role in determining the thermal performance of a building. It has been reported that in Hong Kong, solar heat gain accounts for over half of the total building envelope cooling load. For air-conditioning equipment sizing and analysis, it is customary to neglect the shading effect due to neighbouring buildings and structures. Based on computer energy simulation studies, Lam (2000) pointed out that the total building cooling load and annual building energy use would only be slightly overestimated if the shading effect due to neighbouring buildings was not considered. However, it is believed that there would be variations of energy use on individual floors particularly for daylighting design due to different degrees of external obstruction. Therefore, there is potential to carry out a study of shading effects for building with daylighting controls since electric lighting plays the largest component of the internal load in air-conditioned office buildings.

Although the direct sunlight blockage due to nearby buildings may not be so severe as generally believed, excessive external obstructions to natural daylight from the sky could hinder the performance and effectiveness of a daylighting scheme. This leads building professionals to express a common desire for more information on the energy performance of buildings when daylighting schemes are adopted for commercial buildings affected by various degrees of sky obstruction.

2.3.4 Advanced Solar Film Coating

Daylight, however, is always accompanied by solar radiation. The benefits from daylight may be negated by the corresponding increase in solar heat gain. Moreover, owing to the small angle of incidence, direct sunlight can be excessive for east-facing windows in early morning and west-facing windows in late afternoon. 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 when daylight linked lighting controls are being used (Li et al., 2004). Recent advances in solar film coatings for window glass products provide a means of substantial solar heat reduction due to direct sunlight without affecting the appearance of buildings. Li et al. (2004) also reported that solar film coating provides a means of substantially reducing heat gain without proportionally reducing daylight transmittance. It indicates that the energy expenditure due to lighting and cooling requirements can be minimized under daylighting control schemes, while people can enjoy natural light and maintain good visual contact with the outside environment.

Office buildings using solar film coatings together with a high frequency dimming control gives an alternative option on fenestration design for building designers. The impacts of the solar film coating on daylighting performance and energy issues such as daylight illuminance, solar irradiance, electric lighting load and cooling energy consumption depend upon attending to the subtle interactions of a large number of architectural aspects and building services systems. To have a better understanding of these interactions, on-site measurements together with comprehensive computer simulations should be conducted for the study.

2.3.5 Building Services Performance

Proper daylighting control has a strong potential for reducing energy demand in non-domestic buildings by exploiting daylight more effectively (Li and Lam, 2003a). Energy savings resulting from daylighting mean not only low electric lighting, but also reduced cooling energy requirement (Krarti et al., 2005; Bourgeois et al., 2006; Tzempelikos and Athienities, 2007) and potential for smaller HVAC plants (Lam and Li, 1999). It means that the capital costs of a HVAC system and the accessories including pumps, fans and electrical fittings can also be lowered. Generally speaking, the operating efficiency of a multiple-chiller plant is also subjected to the influence by heat rejection method, load ratio, external conditions and compressor efficiency (Chan and Yu, 2002). The COP of chiller stands is another major factor affecting the energy consumption of the central chiller plant. Poor chiller efficiency is associated with oversized equipment (Li et al., 2003). The accurate prediction of cooling capacity and operating part-load conditions for designing a chiller plant is essential to be determined for an energy efficient building. In the previous research, little work has been done to evaluate daylighting and its energy implications for a full scale commercial building. Moreover, there is insufficient information provided to determine the cooling capacity in varying weather conditions and the chiller performance at various part-load conditions in office buildings, which incorporate a daylight-linked dimming system. It is worth analyzing the annual building energy expenditure and to demonstrate how the cooling requirement is influenced by daylighting schemes.

2.4 Computer Simulation Approach for Energy Analysis in Buildings

In Hong Kong, simulation tools are playing an increasingly important role in the design and engineering of buildings. Computer programs designed for energy modelling and analysis of buildings are generally known as ‘building energy simulation programs’. They are mostly being used for analysing the energy consumption in buildings so as to establish the basis for the four prescriptive building energy codes and the OTTV code. Moreover, in order to holistically consider building energy performance, building energy simulation is also taken as the evaluation method for determining code compliance under the performance-based approach (EMSD, 2003; Hui, 2003). Once established, simulations can provide quantitative energy and cost comparisons among the design alternatives (ASHRAE, 1997). However, the interactions in buildings by their nature are very complex. While some simplified design tools and guidelines exist to help designers understand the phenomena involved, more elaborate, often computer-based tools are required for detailed analysis.

Building energy simulation needs practical experience and skill as there are a lot of subjective judgments on what inputs and methods should be used. Many physical, engineering and numerical assumptions, which are often difficult to justify, have significant influences on the results. There is also considerable controversy about which algorithms and solution techniques are most appropriate to describe the energy flows and building responses. Even though dedicated component modelling algorithms have been used, simulation of the whole building is by no means an exact science when the complex interactions and human behaviour in real life are considered (Hui, 1996). Neither the computer nor the model can completely replace human decisions, judgment, intuition and experience which still play a significant role in determining the validity and usefulness of models (Matko et al., 1992). The merit of the simulation method is to provide a system approach to learn, design, change, optimise and possibly control the behaviour of the system. It is a methodological science in simulation which engineers the building design and enhances the assessment of building performance. Very little work has been done for examination of energy savings from daylighting in high-rise commercial buildings in Hong Kong. A detailed building simulation model facilitates better understanding of the design strategies and system behaviour with respect to energy performance.

2.4.1 Energy Modelling Basics

The common modelling approaches of detailed energy simulation include (a) response function method under time domain, (b) numerical method using finite differences, (c) response function method under frequency domain, (d) numerical method using control volume heat balance and (e) numerical method using a finite element approach (Clarke, 2001). The time-domain response function method is adopted in many simulation programs, such as DOE-2 (Winkelmann, 1993), BLAST (BSL, 1999) and EnergyPlus (LBNL, 2005a). The next one is finite difference approach which is adopted in ESP-r (Aasem et al., 1993; Clarke, 2001); this approach is very general in concept and may produce models whose quality depends heavily on how the schemes are implemented. The other methods are very seldom implemented nowadays for energy simulation of a whole building (Hui, 1996). No definitive statement has yet been made on the performance of different methods when applied in practice.

Hui (1996) mentioned that, in most simulation tools, the building and its energy systems are represented by three basic models:

- Load model – this represents the thermal behaviour of a building's structure and its contents. Building envelope, internal loads and infiltration are considered in the load calculations to determine the amount of heat added to or extracted from the space to maintain designed indoor conditions.

- System model – this represents the thermodynamic behaviour of the air-side or secondary systems. Air handling units, fans and terminal units are simulated to determine the energy required by the system and demands on the HVAC main plant.

- Plant model – this represents the relationship of load versus energy requirements of the primary energy conversion equipment. The fuel and energy required by the main plant (such as chiller and boiler) to meet the building loads are estimated by considering equipment efficiencies and part-load performance.

The most common approach to link these models is the sequential simulation method. In programs with sequential simulation, the building zones, air handling systems, and central plant equipment are simulated sequentially with no feedback from one to the other. The sequential solution begins with a zone heat balance that updates the zone conditions and determines the heating/cooling loads at all time steps. This information is fed into the air handling simulation to determine the system response, but that response does not affect zone conditions. Similarly, the system information is passed to the plant simulation without feedback. This simulation technique works well when the system response is a well-defined function of the air temperature of the conditioned space. Coupling of the models in this way allows solving of the mathematical equations consecutively and serially, thus greatly reducing the efforts for iterative computations.

However, in most situations the system capacity is dependent on outside conditions and/or other parameters of the conditioned space. The zone air temperatures would be affected in practical cases. This does not happen in sequential simulation methods and the lack of feedback from the system to the building can lead to non-physical results. While this enables the affected system or plant components to be properly sized, the system designer would, in most cases, prefer to see the actual change in the zone temperatures. The same mismatches can occur between the system and plant simulations when they are simulated sequentially. To obtain a simulation that is physically realistic, the elements have to be linked in a simultaneous solution scheme (LBNL, 2005a). The entire integrated program can be represented as a series of functional elements connected by fluid (air and water) loops as shown in Figure 2.2. Zone loads calculated at a specified time-step are passed to the building systems simulation module at the same time step. The building systems simulation module calculates heating and cooling system and plant and electrical system responses. Feedback from the systems module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures if necessary. Accurate predictions of space temperatures and systems loads can be achieved by using the integrated solution. The main disadvantage of this scheme, and the reason that it was not widely used in energy simulation tools, is that it demands more computing resources (a high performance workstation is required to reduce the simulation time). However, most current desktop computers can now run programs using the simultaneous approach within a reasonable amount of time.

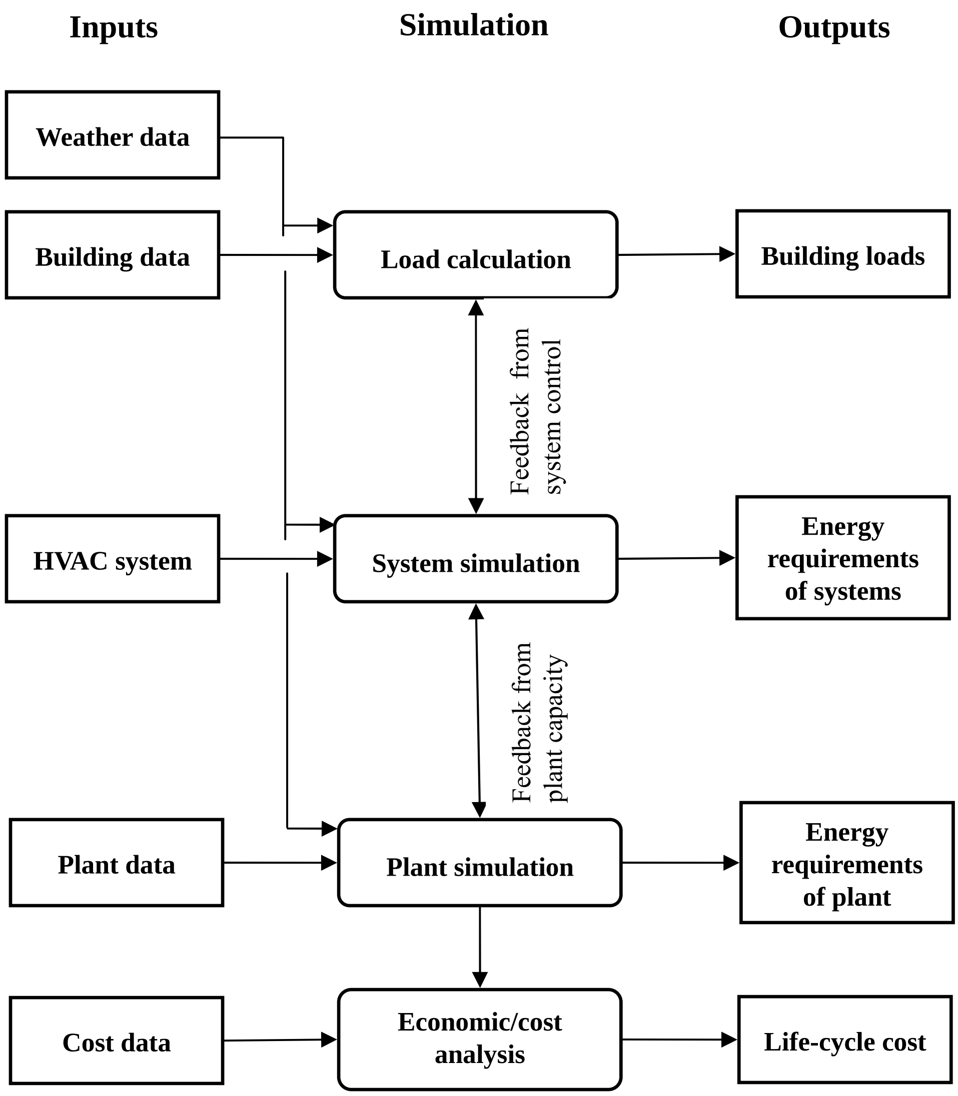


Figure 2.2 Schematic of simultaneous solution scheme

2.4.2 Building Program for This Study

ASHRAE (2005, pp. 32.3) provided some general considerations for selecting energy analysis programs. However, it is hard to judge which program is suitable and adequate for an application since there are no definite criteria to help select the programs wisely in all situations. Generally speaking, each program has its particular features and limitations. The decision for selecting a building energy analysis program depends on its application, simulation time, experience of the users, and hardware available to run it. The most accurate methods for calculating building energy consumption are very time-consuming because of their intense computational requirements and calculation algorithms needed by the designer or researchers. Building energy simulation programs that assemble component models into system models and then using those models with weather conditions and building design data are preferred by experts for determining energy use in buildings. Generally, the detailed simulation programs mentioned in section 2.4.1 (such as DOE-2, BLAST, EnergyPlus and ESP-r) are considered more accurate and capable than those programs using simplified procedures. But a lot of input efforts are usually required by these detailed programs.

The ESP-r simulation program was not considered to be used for this study. The program has no built-in daylighting illumination and calculation models, although Clark et al. (1997) have enabled a run-time coupling between the ESP-r and the lighting application Radiance (Larson, 1993). Very little work has been done for daylight analysis using this program. The main disadvantage of the coupled approach is the maintenance of data and link consistency which are dependent on the separate evolution of each coupled application and making it difficult to achieve any change or improvement (Citherlet et al., 2001).

The other two programs, DOE-2 and BLAST, are widely used throughout the world (Chow and Fong, 1997; Bellia et al., 2007; Crawley et al., 2001a). The main difference between the programs is load calculation method – DOE-2 uses a room weighting factor approach while BLAST uses a heat balance approach. In order to compensate for the lack of interactions between the building and system models in the sequential simulation method, a room weighting factor method is commonly used for adjusting the building loads (Kerrisk et al, 1981; LBL, 1982). This technique works well for cases where the building and system response is well-defined, but it loses accuracy in situations where the response is heavily dependent on the building load and the outside conditions or when the space temperatures are allowed to float drastically (Witte et al., 1989). BLAST uses the heat balance method by setting a control profile to model the system response during the simulation (Taylor et al., 1991). The load simulation is performed first, the space temperatures and building loads are then calculated based on environmental conditions, internal load interactions between zones, infiltration, ventilation and air handling equipment. An energy balance is done to find the space temperature at which the zone load balances with the heating or cooling provided by the system (ASHRAE, 2005). The heat balance method requires more computations at each point in the simulation and careful representation of the heat transfer surfaces and mechanisms. The greatest deficiency of the BLAST program is that there is no built-in daylighting module.

The "EnergyPlus" building energy simulation program developed with support from the United States government was released in April 2001. It was developed based on the most popular features and capabilities of DOE-2 and BLAST (Crawley et al., 2001b; 2004). It uses an integrated simulation method (Figure 2.2) that overcomes the most serious deficiency of BLAST and DOE-2 simulations: inaccurate space temperature prediction due to lack of feedback from the HVAC module on meeting loads. Accurate predictions of space temperatures are crucial for energy efficient system engineering including daylighting schemes – variations of lighting load definitely affect the space temperatures while performing building load and system calculations. The underlying building thermal zone calculation method in EnergyPlus is also a heat balance model. In addition to the integrated simulation method and heat balance calculation for thermal loads, three features are included in the program based on capabilities within DOE-2: daylight illumination (Winklemann and Selkowitz, 1985), WINDOW 5 calculations (Arestah et al., 1994), and anisotropic sky. The daylight effects on building energy performance can be systemically determined. One of the main features in EnergyPlus is that source code of the program can be available and open for public inspection and revision. The users or developers can add their own features and modules within the EnergyPlus structure and framework. A comparison of major features and capabilities of EnergyPlus, BLAST and DOE-2 is shown in Table 2.2.

After reviewing the characteristics of different programs, the building energy simulation program, EnergyPlus, was then selected as the simulation engine in this research because:

- It has become more popular and widely used as a simulation program and its results are generally accepted as reasonable and accurate for different building types and systems (Olsen and Chen, 2003; Ordenes et al., 2007).

TABLE 2.2 Comparison of major features and capabilities of DOE-2, BLAST and EnergyPlus

Features	DOE-2	BLAST	EnergyPlus
Simulation management (loads/systems/plant)	Sequential	Sequential	Integrated, simultaneous solution
Calculation method	Weighting factor	Heat balance	Heat balance
Water loops (connect primary equipment and coils)	No feedback	No feedback	Yes, feedback between system and plant model
Air loops (connect zone air, fans, coils)	No feedback	No feedback	Yes, feedback between load and system model
Window constructions	Use default value	Use default value	Layer-by-layer calculations for custom glazing
Daylight illuminance and Controls (effects of dimming on energy and loads)	Built-in	No daylight module	Built-in
Weather data	Full hourly	Full hourly	Full hourly and sub-hourly
Output method	Standard	Standard	Standard and user-defined results
Add new features and modules by user	No	No	Users can develop their own models

- It can offer a wide range of special features for a detailed whole-building energy performance analysis – particularly for daylight analysis which will be studied in this research (Li et al., 2006; Loutzenhiser et al., 2007).

- In addition, the software has also been tested and validated with other simulation programs for accuracy (ASHRAE, 2001; Witte et al., 2001, Neymark et al., 2002).

- The external obstructions of the site (i.e. real urban context) can be modelled to account for shading effects for individual floors, particularly for daylighting designs (Li and Wong, 2007).
- EnergyPlus is also recognised by the PB-BEC in Hong Kong as an acceptable simulation tool (EMSD, 2003).
- EnergyPlus has its source code distributed to third-party users who are interested in developing an interface that provides input to and read output from the program and adding new modules to the program (LBNL, 2005b, Li et al., 2008).

2.4.3 Performing the Analysis

Much of the success of modelling relies on the backgrounds of the people involved, who require both sound engineering knowledge and a good measure of computing ability (Logan, 1993; DOE, 2001). To build up simulation skills, Hui (1998) mentioned seven essential steps as a good guideline for successful analysis:

- Step 1 – Defining the problem
- Step 2 – Specifying the model
- Step 3 – Data acquisition
- Step 4 – Implementation
- Step 5 – Planning

- Step 6 – Experimentation

- Step 7 – Analysis of results and reporting

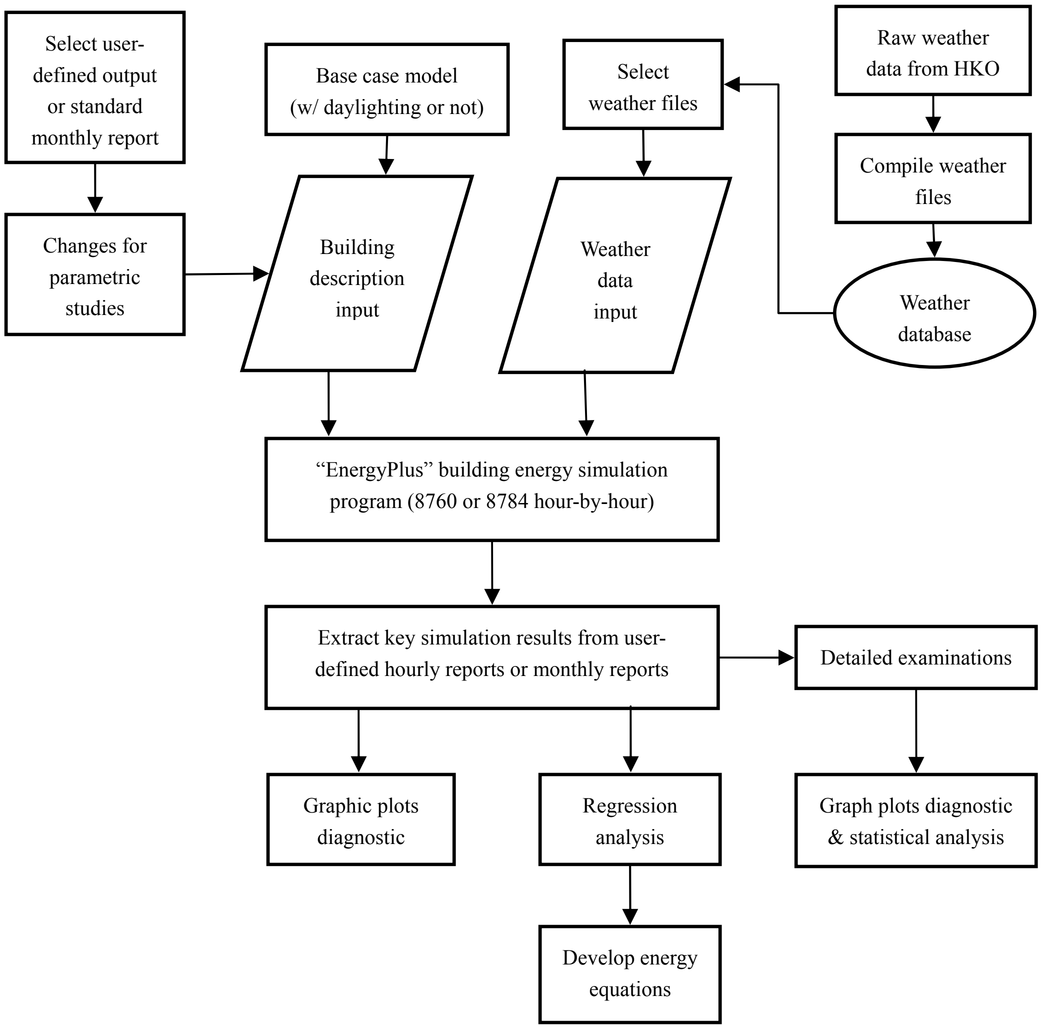


Figure 2.3 Building energy simulation and analysis process

An overview of the building energy simulation and analysis process developed in this research is illustrated in Figure 2.3. A base-case building model, outdoor design conditions and typical weather files were established for the computer simulations in the following chapter. In addition, experimental or measuring data were recorded to compare with the simulation results for validation of the software. Daylighting designs and their energy implications were also predicted and discussed via a series of simulations. Common techniques used for performing analysis using the simulation in this study include:

- Parametric runs for design options
- Regression analysis for developing energy equations
- Graphical methods for engineering checking

To standardize and simplify the simulation process, the procedure for creating and running the parametric simulations was automated as much as possible. It was found that the selected program was designed to perform parametric studies efficiently. EnergyPlus allows simulation runs in batch mode, either for parametric runs or for multiple weather files. The program extracts the user-defined results, stores and handles the large volume of simulation inputs and outputs.

Chapter 3 Base-Case Model and Weather Database

3.1 General

The study of building energy performance, application of building designs and evaluation of daylighting performance can be assessed via computer simulation software. The selected building energy simulation program, EnergyPlus, incorporates sets of mathematical models that seek to explain quantitatively how each component of a building behaves under certain indoor and outdoor circumstances. Building models and weather files are often used as the input databases in computer simulations. The reference building approach serves to link the component performance standard to the whole-building energy performance standard (ASHRAE, 2000). A reference (base-case) office building was created for this research study to serve as a benchmark or base-case for comparison and evaluation of daylighting schemes. Development of reasonable, standardised input data for the reference building is essential and actual electricity use can be estimated through use of realistic design criteria on different building designs and system applications.

Outdoor design conditions such as air temperature and solar radiation are commonly used for design and sizing of HVAC systems (Lam and Hui, 1995). If climatic factors influential to the system have been considered properly, the building will be able to handle the actual operating conditions effectively. Therefore, the accurate prediction of energy performance can also be estimated (Hong et al., 1999). Therefore, there is a need to establish more comprehensive data on more recent and long-term weather information for building system applications at acceptable risk levels. Weather data is also required for building energy simulation and analysis to serve as input for driving the thermal models within the simulation tool. For comparative studies and long-term energy estimation, a yearly weather database representative of prevailing climatic conditions is often used (Yang et al., 2008). The required weather data depends on the type of simulation tool and the objective of the study, particularly for daylighting analysis in this research. However, it is important to ascertain whether the typical weather year data can produce simulation outputs that are close to the long-term mean.

3.2 Reference Building Approach

Development of building descriptions that reasonably represent the energy-related features of the building stock is critical to comparing and evaluating energy performance among design options. Descriptions of the reference building is designed with its envelope, building elements and energy-consuming systems conforming to the prescriptive requirements, and also used for compliance purposes in the standards with the whole-building performance path (Hui, 2003). However, some input parameters which have not been mentioned in the prescriptive energy codes might be required to define the modelling assumptions according to professional experience and local engineering practice.

3.2.1 General Building Characteristics

The reference office building developed for the computer simulation was based on previous surveys for building descriptions, design requirements provided in building energy codes and professional judgments. Local offices are graded A, B or C by the Rating and Valuation Department (RVD). Grade A office buildings of high-quality finishes and effective central air-conditioning systems amounted to 91,500m^2, or 85% of the total office completions in 2006. Moreover, the stock of Grade A office space at the end of 2006 stood at 5,799,200m^2, representing 59% of the total office stock (RVD, 2007). The reference office building was considered to be developed from the quality equivalent to the luxurious Grade A offices for this study. The other major features in medium to large commercial buildings in Hong Kong are also summarised as follows:

- Details of a total of eight Grade A office buildings, three from Yu and Chow (2001) and five from Lam et al. (2004), respectively, were analysed. It can be seen that all the buildings are high-rise with an average number of floors of forty-one.

- Curtain wall construction and reflective glazing are often installed for Grade A office buildings (Chan and Chow, 1998).

- An air-cooled heat rejection method for central cooling plant is almost always used (Yik et al., 2001).

- A variable-air-volume (VAV) system is a common design for Grade A office buildings for better control of each air-conditioned zone as well as for better energy efficiency (Yu and Chow, 2001).

3.2.2 Building Envelope Construction

Building envelope characteristics of sixty-four commercial buildings were recorded by Chan and Chow (1998) in Hong Kong. Lam et al. (2004) also reported the construction details of twenty buildings in the public sector. Building envelope construction details and thermal properties of the eighty-four commercial buildings were analysed and summarised. Table 3.1 illustrates a comparison of the major building envelope parameters between the base-case model and the results from the two surveys. The envelope design of the base-case model had the thermal properties very close to the means and median of the survey results. The floor-to-floor and window heights of the base-case model were 3.5 and 1.5m, respectively. This represented a WWR of 43%. Glazing was single reflective glass with an SC of 0.4 and LT of 0.3. The U-values for the roof, external walls and single glazing windows were 0.54, 2.05 and 5.6W/m^2°C, respectively. Using the above building envelope design parameters, the calculated OTTV of the reference building was 30W/m^2, which also just complied with the local OTTV standard (BD, 2000). This also represents the fact that the reference building satisfied the basic requirement of envelope design in the PB-BEC (EMSD, 2003).

TABLE 3.1 Comparison of the envelope parameters for the base-case model

	Window shading coefficient	Wall U-value ($W/m^{2}°C$)	Window-to-wall ratio
Maximum	0.95	3.50	0.83
Minimum	0.18	0.70	0.18
Mean	0.49	1.81	0.46
Median	0.43	1.90	0.44
Base case	0.40	2.05	0.43

3.2.3 Building Systems Design

Recent work on the electricity end-use load characteristic of high-rise cooling-dominated office buildings has revealed that office appliances account for, 15-25% of total building electrical demand (Lam et al, 2003). With the exception of air-conditioning systems and artificial lighting installation, it is the third largest electricity-consuming items in commercial buildings. Therefore, a set of realistic design criteria for lighting and miscellaneous power is important to building service engineers. With such data, more realistic cooling load requirement and energy prediction for lighting installation, air-conditioning systems and office appliances can be derived. Table 3.2 gives the designed internal densities and recommended figures from the relevant literature. The lighting code (EMSD, 2007c) suggested that the maximum allowable lighting power density (LPD) of $20W/m^2$ was recommended for lighting design to satisfy the required indoor illuminance. This value is always used in thermal load calculations by local building engineers. Two surveys for installed LPD for office buildings in Hong Kong were reported. Lee et al. (2001) suggested that $18W/m^2$ should be considered as the realistic design criteria for LPD in building design, while Lam et al. (2004) found that the average LPD of 20 office buildings was 23.7W/m^2. After engineering judgment, an LPD of 20W/m^2 was used in cooling load and energy estimations for the reference office building.

TABLE 3.2 Comparison of the system parameters for the base-case model

	Lighting power density (W/m^2)	Equipment power density (W/m^2)
Recommended by energy codes	20.0 (EMSD, 2007c)	10.0 (EMSD, 2005)
Surveyed by Lam (2004)	23.7	20.2
Recommended by Lee (2001)	18.0	20.2
Base case	20.0	18.0

With the advent of computer technology, especially microcomputers in the 1980s, computers and peripheral devices have widespread use in the office environment. Local engineers adopt higher heat-gain criteria for appliances in cooling load estimation. Because of continuing advances made in electronic technology, the power rating and, hence, actual electrical power consumed is trimmed gradually. Equipment power density (EPD) of 10W/m^2 is recommended for building energy simulation in the PB-BEC. Previous research studies revealed that EPD of 20.2W/m^2 was the average value of the surveyed buildings and can be used as a design criteria for energy prediction in Hong Kong (Lee et al., 2001; Lam et al., 2004). However, there is no general guideline on the design criteria to be used. The engineers should be responsible for deciding the design value that matches the actual usage conditions in a building. Equipment reflects the number of occupants sharing the use of an office area. The realistic design value for office equipment load can be determined by multiplying the occupancy density by the power demand of individual equipment. The proposed design criteria of 18W/m^2 for office equipment was estimated based on measured office appliance energy use in the recent research (Wilkins and Hosni, 2000).

Package air-cooled chillers of COP of 2.9 were selected for the base-case model, which fulfilled the minimum efficiency in the air-conditioning code (EMSD, 2007d). The indoor air temperature was maintained at 24ºC for the purpose of sizing air-side and water-side equipment (EMSD, 2005; 2007d). The building and its HVAC system operate 10 hours per day (08:00 to 18:00) and five and a half days per week, which is very common in Hong Kong.

3.2.4 Office Building Model

After consolidating the above design considerations, the base-case reference building developed in this research was basically a 40-storey square commercial building (35m x 35m) with curtain wall construction and a centralised HVAC system. The total gross floor area and air-conditioned area were 49,000 and 41,160m², respectively. The air-conditioning plant was a VAV system and the chillers were of a packaged air-cooled screw type to be used in the building. Figure 3.1 shows the typical floor plan and section of the building. A summary of the key parameters of the reference building is presented in Table 3.3. The base-case model was used as a baseline for comparing energy performance with various building designs in this research. It is believed that the base-case building model can represent a typical office building in the urban district in Hong Kong. The details of the EnergyPlus input file for the base-case office building can be found in Appendix I.

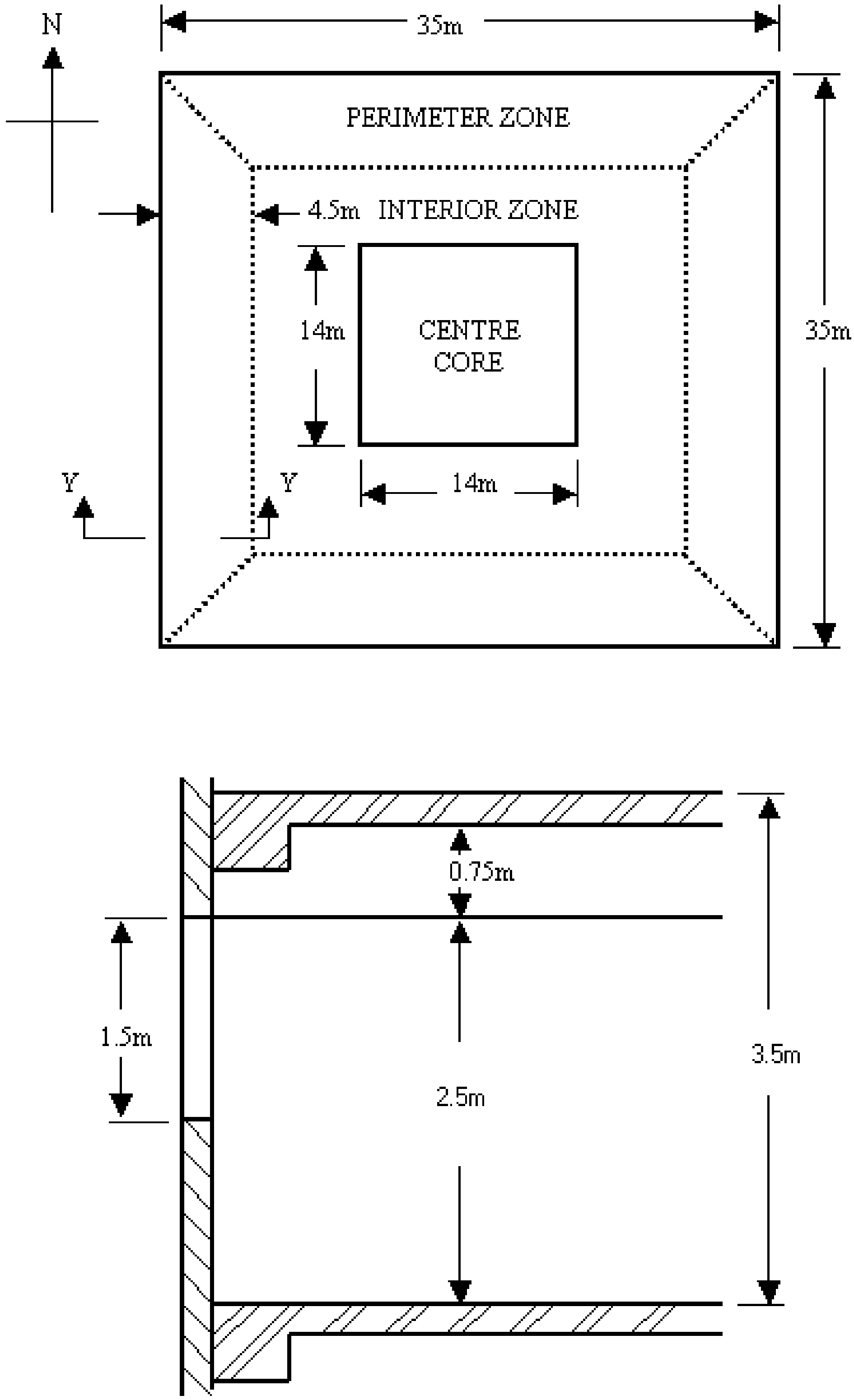


Figure 3.1 Plan and section of generic office building

TABLE 3.3 Descriptions of the base-case office building

General Information	
Location:	Hong Kong Special Adminitrative Region (latitude 22.3° N, longitude 114.2° E)
Building type and storeys:	Office building, 40 storeys above ground
Floor areas:	Total gross floor area = 49,000m^2 Air-conditioned area = 41,160m^2
Dimensions and heights:	35 m x 35m (square); floor-to-floor = 3.5 m; window height = 1.5 m; window-to-wall ratio = 0.43
Operating hours:	Mon. to Fri.: 8:00 – 18:00; Sat.: 8:00 – 13:00 Sun & holidays: closed
Building Constructions	
building envelope:	
(a) External walls :	(spandrel portion of curtain wall) - 6mm glass + 25mm airspace + 200mm n.w. concrete + wall paper (U-value = 2.05 W/m^2°C)
(b) Roof:	13mm slag + 10mm roof build-up + 50mm roof insulation + 200mm n.w. concrete + ceiling void + 19mm ceiling panel (U-value = 0.54 W/m^2°C)
(c) Windows:	6mm reflective single glazing (SC = 0.4, LT = 0.3, U-value = 5.6 W/m^2°C)
Internal structure	
(a) Floor:	(Typical middle floor) carpet + 50mm screeding + 150mm l.w. concrete + ceiling void + 19mm ceiling panel (U-value = 0.60 W/m^2°C)
(b) Internal core wall:	50mm mosaic tile + 19mm cement mortar + 200 h.w. concrete + 19mm plaster + wall paper (U-value = 1.93 W/m^2°C)
(c) Internal partitions:	16mm gypsum board + 25mm airspace + 16mm gypsum board (U-value = 1.68 W/m^2°C)
Design Parameters	
(a) Building load: Occupancy density = 8 m^2/person Lighting load = 20 W/m^2; Working plan illuminance = 500 lux Office equipment load = 18 W/m^2 Infiltration = 0.6 air change per hour (ACH) during cooling plant off period	
(b) HVAC system: Air-side system type = VAV with terminal reheat Fresh air flow = 8 L/s/person Thermostat setpoints – cooling = 24 ºC, heating = 21 ºC Throttling range = 1 ºC	
(c) HVAC refrigeration plant: Type and numbers of chiller = 6 nos. of package air-cooled chiller with screw compressor Chiller coefficient of performance = 2.9 (at design condition of 35 ºC outdoor air temperature)	

3.3 Outdoor Design Conditions

To evaluate the energy performance of buildings, proper design and selection of air-conditioning systems are essential. As central cooling plant together with air handling units and chilled water pumps contribute about half of the total electricity consumption in office buildings in Hong Kong, an accurate cooling load calculation method should be performed and applied to enhance the operating efficiency of air-conditioning components (Mui and Wong, 2007). Simple thermal load calculations such as the CLTD/SCL/CLF method (ASHRAE, 1993), rules of thumb (i.e. cooling requirement per unit area, W/m^2) (Yu and Chow, 2000) and commercial-based simulation programs (i.e. TRACE 600 and E-20) are commonly applied throughout the building design process, particularly during the initial design stage. With powerful computer development, the subject of building energy simulation, which provides effective design decision support and energy conservation measures (ECMs), has been becoming more and more popularly used in building project developments in recent years (Pan et al, 2007).

The climate of a particular location tends to influence the shapes and forms adopted for building design, and dictates the types of environmental control required. In subtropical Hong Kong, the main building design strategy is to reduce cooling requirements during the long, hot and humid summer period. Key climatic variables affecting building cooling energy are temperature, moisture content and solar radiation (Lam et al., 1992). Dry-bulb temperature determines summer conduction heat gain while solar radiation and wet bulb temperature are two parameters crucial to the solar heat gain and latent load calculations, respectively. The peak cooling requirement of a building strongly depends on the external weather conditions (Lam and Hui, 1996a). The usual practice for the design of an HVAC system involves computation of peak design load at a specific hour of a design day based on the required indoor and prevailing outdoor design conditions. Weather data representing severe climatic conditions are employed in the load calculations for determining peak design loads and the appropriate capacity of HVAC plants. Data for outdoor design conditions are usually determined by statistical analyses of long-term meteorological records collected from local weather stations. As developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), dry-bulb temperature for the summer frequency of 2.5% and its coincident wet-bulb temperature are the design criteria for HVAC applications (ASHRAE, 1993). A recent study on long-term (1979-96) outdoor temperatures has revealed that 32°C dry-bulb and 26.9°C wet-bulb temperatures are the recommended summer 2.5% significance level design conditions for subtropical Hong Kong (Lam and Hui, 1995). In determining solar heat gain, calculations are usually based on the assumption that the building is under a cloudless day. Accordingly, design data such as solar heat gain factors (SHGFs) are computed based on the solar intensities of a clear sky. These data, which are considered as the maximum solar heat gains, are adopted together with the outdoor design temperatures in the maximum load determination and plant sizing. However, this design weather data representing extreme climatic conditions may not occur at the same time. It has been reported that independently determined design weather conditions are more stringent than their corresponding coincident values, and can lead to over-sizing of the HVAC plants (Lam and Hui, 1995).

Analysing the thermal load of a building involves understanding the complex heat transfer relationships between the external environmental characteristics and the building parameters, even for buildings that incorporate daylighting controls. Previous research indicated that building peak loads would be reduced while incorporating daylighting design in building and weather conditions also play an important role in determining the peak cooling plant capacity (Li et al., 2005). It has also been reported that building cooling loads computed by simulations based on local weather data can form a good basis for plant sizing (Yik et al., 1998). The HVAC system and equipment type of the designed building (with daylighting controls) should be the same as the reference building (without daylighting controls) in the total energy budget approach (EMSD, 2003). Therefore, the designed cooling load for sizing of water-side and air-side equipment was estimated based on the reference case in this study. The influences of critical climatic data on the building cooling load determinations can be studied through computer building energy simulation techniques.

3.3.1 Cooling Load Breakdown

The generic commercial office building was used for the analysis. The EnergyPlus package conducts hour-by-hour calculations, using 8,760 hourly records of measured weather data including air temperatures and solar radiation to analyse building energy performance of a particular building design for a whole year. Systematic data measurement is regarded as the most effective and accurate method of setting up the required weather database. The Hong Kong Observatory (HKO) is the local weather station. Weather data used for computer simulations have been collected from the HKO such as dry bulb temperature, horizontal global radiation, sunshine hour, cloud cover, wind speed, etc. (HKO, 1979-2005). Climatic conditions, however, vary from one year to another. The number of years for which weather data is available will determine the reliability of the weather database. In principle, as many years as possible should be considered. The longer the period of records, the better and more representative the results will be (since shorter periods may exhibit variations from the long-term average). In total, twenty-seven weather data sets were compiled for Hong Kong using the measured hourly data from the individual yearly weather record from 1979 to 2005 as local measurement of hourly global solar radiation started in December 1978 (Lau, 1989). The simulated results are used to establish correlation models between design climatic data and cooling requirements.

A series of computer simulations based on the weather data sets from 1979 to 2005 was conducted. The components in peak cooling load based on the weather data of year 2005 are shown in Figure 3.2. The peak cooling load was broken down into seven components, which were grouped into two categories, internal cooling load (ICL) and building envelope cooling load (BECL). The ICL includes occupancy load, lighting and equipment. The other items, such as window solar heat, glass conduction, wall conduction and roof conduction, were grouped together as BECL. The roof has a 50mm thermal insulation with no skylight and the U-value is only $0.54 W/m^2 °C$. As the generic building is a high-rise of 40 storeys, the roof area is very small compared with the total building envelope. Consequently, the roof conduction contributes only 0.2% to the building cooling load. The computed ICL and BECL account for 58 and 42% of the total loading, respectively. Similar patterns were observed for the other years. Although heat gain through the building envelope is not the majority, its effect on peak cooling load calculation and plant sizing is still significant. Appropriate selection of outdoor design conditions, therefore, forms an essential part of energy-efficient building designs.

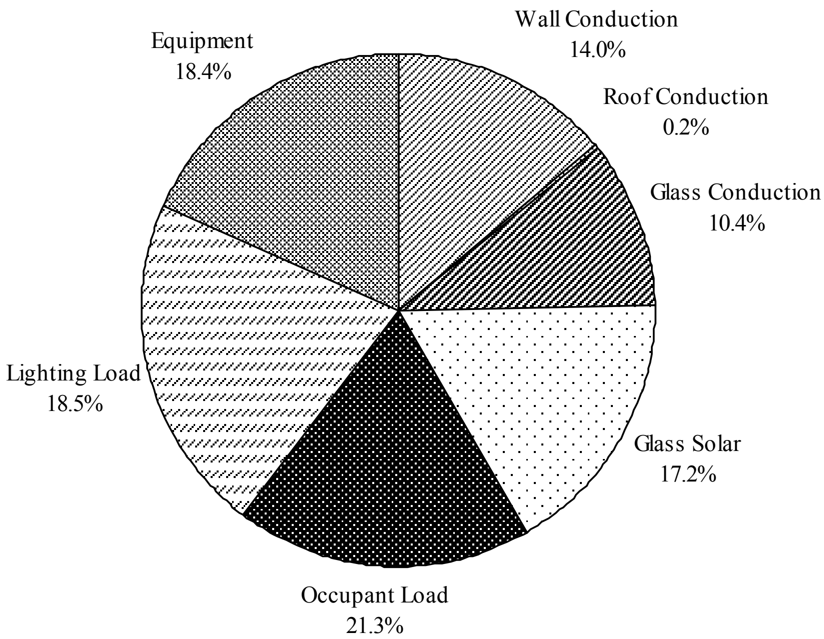


Figure 3.2 Breakdown of peak cooling load for the base-case generic office building

3.3.2 Monthly Cooling Loads

Figure 3.3 presents the range of the computed average hourly cooling load profiles including the long-term average based on the twenty-seven weather data sets. The monthly cooling loads vary from one year to another but similar patterns can be observed for all years. The minimum and maximum monthly differences between these 27 years are 203 and 523 kW, respectively, representing 8.5 and 21.9% of the 27-year long-term mean monthly cooling load of 2,379kW. The larger differences tend to appear between February to April (i.e. spring) when the local weather is considered unstable (Li et al., 2002b). The peak cooling load is observed in July and the major cooling demands occur between June and September. These agree with the past study (Li and Lam, 1999) on the long-term weather data analysis that June, July, August and September are the four-month summer for Hong Kong in cooling load analysis. For designing air-conditioning systems, the outdoor design data were determined based on the local summer period. Again, this supports the fact that the climatic conditions strongly influence the cooling load computation.

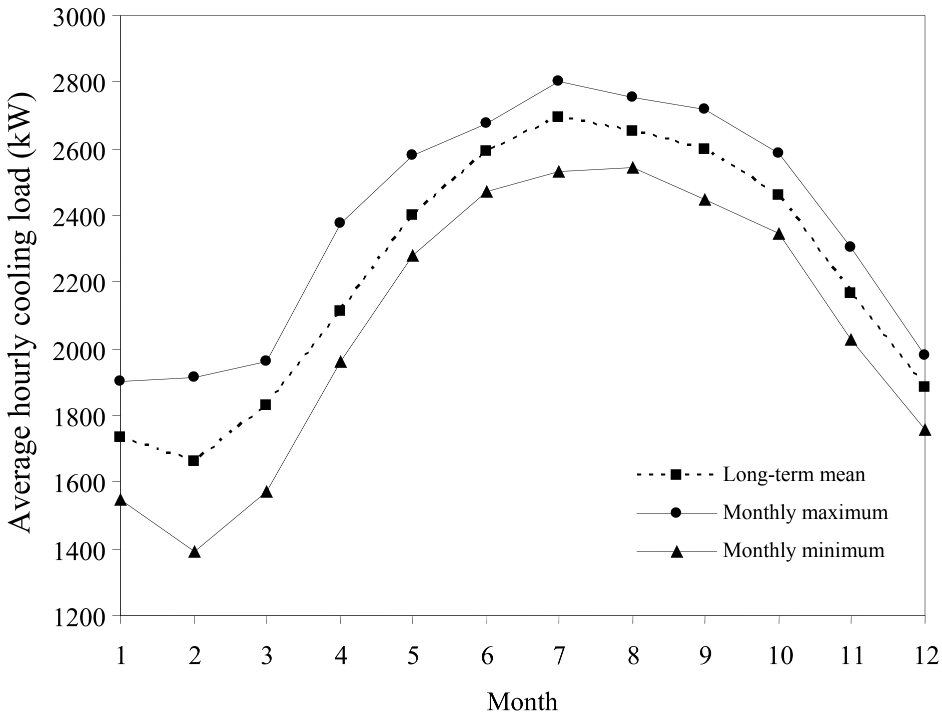


Figure 3.3 Average hourly cooling loads (1979-2005)

3.3.3 Peak Cooling Load for Individual Years

To get a better idea about the effects of weather data on the peak cooling load, the simulated data were analysed at Figure 3.4. A constant ICL of 2,064kW can be found for all 27 years. The variations in peak cooling load are thus due mainly to the BECL, which is climate-dependent. The peak cooling load varies from the highest of 3,618kW in 1979 to the lowest of 3,502kW in 1985. In terms of load per unit gross floor area, this represents 71-74W/m², which is within the rule of thumb check figures used by local building engineering practices. The standard deviation is only 26kW, which accounts for only 0.73% of the 27-year long-term average of 3,548kW. The small variation shows that the extreme weather conditions occurring in each year are quite close.

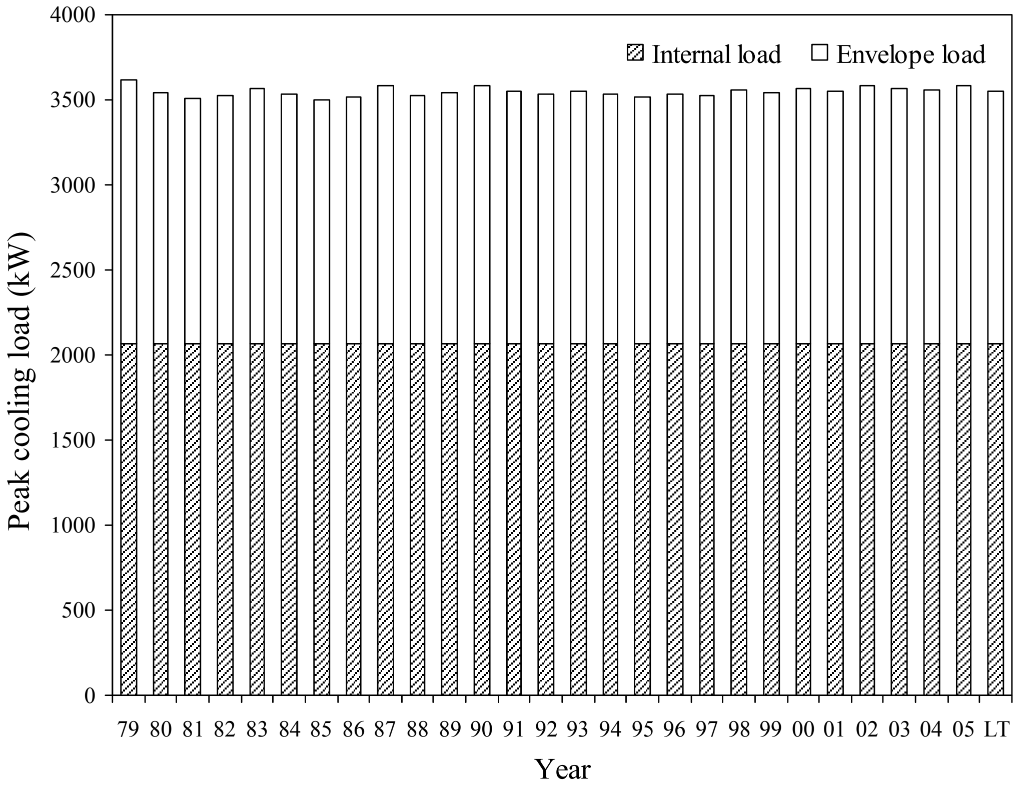


Figure 3.4 Peak annual cooling loads (1979-2005)

3.3.4 Peak Cooling Load Analysis

For a building with steady internal load characteristics, the peak cooling load would be the time corresponding to the maximum heat gain through the building envelope. The HVAC system design and energy estimation for buildings, therefore, depend very much on the design weather data. The results of incorrect selection of climatic conditions can be costly when system and plant operation are considered. If some very conservative, extreme conditions are taken, uneconomic design and oversizing may result. If design loads are underestimated, equipment and plant operation will be affected. If a climatic factor influential to the system has not been considered properly, the building may not be able to cope with the actual operating conditions sufficiently. There is no uniform basis for defining the system reliability of individual design weather variables and their impacts on building performance. The design load is the load, which will only be exceeded for reasonably small percentages of time, such as 1, 2.5 or 5% of a certain period. The four-month summer period (from June to September) is adopted for the present study.

For a particular building type, the heat flow through the external building envelope depends on the outdoor weather conditions. Criteria for outdoor design conditions should be determined according to the applications and category of importance of the system and the building considered. The weather data representing severe climatic conditions are employed in the design of peak load calculations. As indicated in Figure 3.2, the BECL is mainly made up of three main components (i.e. ignoring the roof conduction) namely, wall conduction (Q_w), glass conduction (Q_g) and glass solar heat gain (Q_s). Mathematically, it can be expressed as:

$$\begin{aligned} \text{BECL} &= Q_w + Q_g + Q_s \\ &= (A_w \text{ x } U_w \text{ x } T_{clw}) + (A_g \text{ x } U_g \text{ x } T_{clg}) + (A_g \text{ x SC x SCLF}) \end{aligned} \quad (3.1)$$

$$\text{BECL}/A_{tw} = [(1\text{-WWR}) \text{ x } U_w \text{ x } T_{clw}]+(\text{WWR x } U_g \text{ x } T_{clg})+(\text{WWR x SC x SCLF}) \quad (3.2)$$

where A_g = Area of glazing (m²)

A_{tw} = Total gross exterior wall area (m²) = $A_g + A_w$

A_w = Area of opaque wall (m²)

SC = Shade coefficient (dimensionless)

SCLF = Solar cooling load factor (W/m²)

T_{clg} = Cooling load temperature difference for opaque wall (°C)

T_{clw} = Cooling load temperature difference for glazing (°C)

U_g = U-value of glazing (W/m²°C)

U_w = U-value of opaque wall (W/m²°C)

WWR = the ratio of window to gross wall area (dimensionless)

It can be seen that the higher the climatic parameters T_{clw}, T_{clg} and SCLF become, the larger BECL will result. The T_{clw}, T_{clg} and SCLF data at a particular latitude and time of year can be found from design manuals (McQuiston and Spitler, 1992). These data, which are considered severe conditions, are employed by building designers for peak load determination and plant sizing. However, climatic variables are locality-dependent in addition to the expected variations due to latitude and season. It would be more appropriate and useful to obtain local climatic data for design. The computer package EnergyPlus used in this study performs hour-by-hour computations of the cooling loads. Hourly values of Q_w, Q_g and Q_s can be obtained from the computer simulation results. As building parameters A_g, A_w, U_g, U_w and SC are constant input data, the corresponding hourly T_{clw}, T_{clg} and SCLF, therefore, can be determined using Equation 3.1. The BECL and its corresponding coincident T_{clw},

T_{clg} and SCLF for the summer months at significance levels up to 10% were determined based on the simulation results and are shown in Table 3.4. It can be observed that the T_{clw}, T_{clg} and SCLF fluctuate at different significance levels. However, a decreasing trend can be noticed for these three climatic variables as the significance levels rise. The BECL, T_{clw} and SCLF have similar patterns, which drop to about 80% of the corresponding peak values at the 5% or 10% significance level.

TABLE 3.4 Building envelope cooling load and the coincident climatic data at different significance levels

	10%	5%	2.5%	1%	0.5%	0.1%	Peak
BECL (W/m²)	59.3	65.0	68.1	71.2	72.3	74.1	77.7
T_{clw} (°C)	16.7	19.2	19.7	20.5	21.2	21.4	22.4
T_{clg} (°C)	5.0	6.9	6.7	7.4	7.7	7.9	8.3
SCLF (W/m²)	155.9	151.6	168.7	171.8	169.2	175.4	184.2

For the T_{clg}, it goes down to about 60% of the peak value is at the 10% significance level. Extreme weather conditions contribute large cooling load. However, using such severe situations, which scarcely occur, may result in uneconomic design and over-sizing. To demonstrate clearly the climatic effect, each parameter was normalised to its individual maximum value. The normalised simulated BECL and the coincident normalised climatic parameters (i.e. T_{clw}, T_{clg} and SCLF) for the summer season are plotted against the significance levels up to 10% in Figure 3.5. Several features can be identified. In general, all the four components tend to increase as the significance level reduces. At peak cooling load, all the weather parameters are close to their individual maximum values. This means that a large cooling load is contributed by an extreme weather condition. However, different patterns are observed for different parameters. A wide variation is found for T_{clg}. At a significance level of 8%, the normalised reading can vary between just under 73% to about 84% of its peak value. For the T_{clw} and SCLF, they seem to exhibit smaller variations. A higher T_{clw}, however, corresponds to a lower SCLF and vice versa, indicating a reverse trend. These show that the three weather parameters do not increase at a constant rate as the design BECL does.

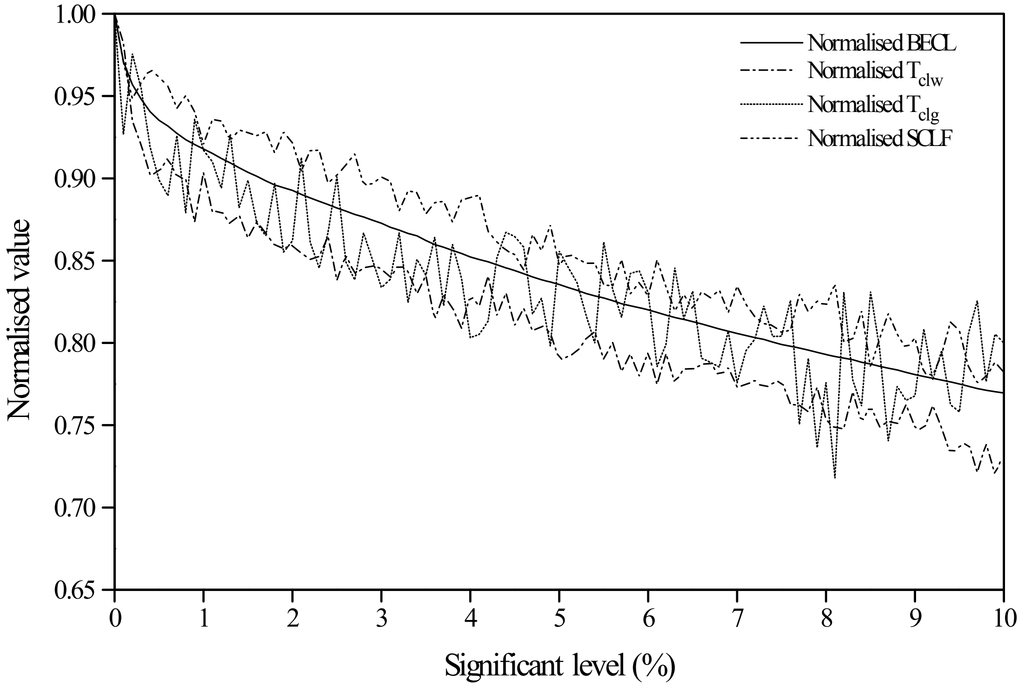


Figure 3.5 Normalised BECL, T_{clw}, T_{clg} and SCLF at different significance levels

The weather data (i.e. T_{clw}, T_{clg} and SCLF) employed in the building envelope calculations (i.e. Equation 3.2) can be derived based on the hourly simulation results and multiple regression techniques. To generate data for deriving algebraic expressions, a total of 27 simulation runs with the building envelope being changed systematically were conducted. Table 3.5 gives the perturbation values of the parameters used for the simulations. Hourly weather data of 1989 was used to carry out the hour-by-hour simulations. The year 1989 is considered the test reference year (TRY), in that the measured meteorological data represent the prevailing local

TABLE 3.5 Perturbation value for multiple regression analysis

Building load	U_w (W/m²°C)	SC	WWR
(3^3=27 runs)	2.28	0.8	0.6
	2.05	0.4	0.43
	1.49	0.2	0.2

climatic conditions with respect to building energy performance analysis (Hui and Lam, 1992). By multiple regression with the least-squares fitting method, the coefficients T_{clw}, T_{clg} and SCLF at different significance levels were determined. Table 3.6 shows the regression statistics. The 'goodness of fit' of each equation is measured by the coefficient of determination (R^2). The R^2 values for different significance levels exceed 0.99 indicating that over 99% of the changes in BECL can be explained by the variations in T_{clw}, T_{clg} and SCLF. From the F-test, F-values range from 2.636 to 3.477. The critical value of the F-distribution for a significance level of α=0.01 is 4.76, which is very much smaller than the calculated F values (McClave and Sincich, 2006). In other words, less than 1% of the time, by chance, the null hypothesis of no linear regression between BECL and the three building parameters (i.e. (1-WWR)U_w, (WWR)U_g and (WWR)SC) is true. Hence, it is reasonable to assume that the regression equation is appropriate in describing the BECL as a function of these building parameters. Student's T-test values are used to test the confidence and significance of the regression coefficients (i.e. T_{clw}, T_{clg} and SCLF). The critical value for the one-tailed test on T_{clw}, T_{clg} and SCLF using a significance level of α=0.0005 is 3.767 (Jarrett and Kraft, 1989). It can be seen that the SCLF has the largest statistically significant effect on the BECL, followed by the T_{clw}, then the T_{clg}. All the T values are far greater than 3.767. Hence, the null hypothesis that T_{clw}, T_{clg} and SCLF=0 can be rejected at the 0.0005 significance level.

In other words, the regression coefficients for the three building parameters (i.e. (1-WWR)U_w, (WWR)U_g and (WWR)SC) are statistically significant at the 0.0005 level.

TABLE 3.6 Multiple regression statistics for the building and climatic variables

Significance level	R^2	Regression coefficient			F	T		
		T_{clw}	T_{clg}	SCLF		(1-WWR)U_w	(WWR)U_g	(WWR)SC
Peak	0.9974	21.8	7.6	180.2	2941	196	60	243
0.1%	0.9973	21.7	7.5	178.5	2832	183	55	225
0.5%	0.9971	21.3	7.3	174.2	2636	161	48	197
1%	0.9976	20.7	7.1	172.3	3187	211	63	263
2.5%	0.9978	20.2	7	166.4	3477	234	71	289
5%	0.9972	19.5	6.8	159.1	2730	177	54	215
10%	0.9971	17.8	6.5	145.9	2636	165	53	203

To assess whether the regression equations are applicable to other weather years, mean-bias errors (MBE) and root-mean-square errors (RMSE) were calculated. Mean bias errors and root-mean-square errors are defined as follows:

$$MBE_j = \frac{\sum_{i=1}^{27}(x_i - y_{ij})}{27} \tag{3.3}$$

where x_j = predicted peak BECL at the significance level j (j = 1 to 7)

y_{ij} = simulated peak BECL at the significance level j for the individual year i (i = 1 to 27)

$$RMSE_j = \sqrt{\frac{\sum_{i=1}^{27}(x_i - y_{ij})^2}{27}} \tag{3.4}$$

A positive MBE indicates that the predicted BECL values are larger than the simulation results and vice versa, and RMSE is a measure of how close the predicted BECL data are to the simulation values. Table 3.7 presents the MBE and RMSE for

BECL at significance levels up to 10%. It can be seen that the MBE ranges from 0.81/m² at peak level to 1.48W/m² at the 10% significance level, representing 1.1 and 2.5% deviations, respectively. The RMSE of 1.58W/m² occurs at the peak level and the largest RMSE of 2.76W/m² appears at the 10% significance level. These show that using the proposed climatic parameters can obtain accurate simulation results. In general, the two errors rise as the significance levels increase. This is due mainly to the large variations of the design weather conditions at high significance levels.

TABLE 3.7 Summary of MBE and RMSE at different significance levels

Significance level	MBE (W/m²)	MBE (%)	RMSE (W/m²)	RMSE (%)
Peak	-0.81	-1.07	1.58	2.09
0.1%	-0.55	-0.73	1.48	1.99
0.5%	-0.17	-0.24	1.54	2.13
1%	-0.30	-0.42	1.65	2.32
2.5%	0.54	0.78	2.06	3.02
5%	1.24	1.91	2.63	4.03
10%	1.48	2.46	2.76	4.61

In Hong Kong, solar radiation intensities used in the design load calculation are based on the assumption that the building is under a clear sky with the clearness number of unity and the SCLF data extracted from the design manual (McQuiston and Spitler, 1992) accordingly. For design temperature criteria, most designers tend to take 33°C dry-bulb and 28°C wet-bulb for summer as the rule of thumb design figure. As suggested by local air-conditioning design guideline (EMSD, 1998c), 33.5°C dry-bulb is usually adopted for projects of the Hong Kong Special Administrative Region Government. Recently, a study on long-term weather records of Hong Kong has recommended that 32°C dry-bulb and 26.9°C wet-bulb are for general HVAC design (2.5% significance level) and 32.6°C and 26.9°C wet-bulb are for critical processes (1% significance level) (Lam and Hui, 1995). Different design criteria used for cooling load calculations will give different results. The BECL based on these suggested outdoor design conditions were determined and are listed in Table 3.8. It can be seen that all the BECL values computed are greater than the peak value using the simulation technique. The T_{clw} ranges from 23.9 to 25.4°C, which is about 3°C above the T_{clw} for the simulated peak BECL. The T_{clg} is around 10°C, which is overestimated by about 30% in the simulation results. The SCLF adopted for each case is 218W/m², which is 34W/m² more than the SCLF for the peak simulated BECL. Among the three components of heat gain, SCLF is the main contributor to the large BECL. It shows that more work should be done in order to establish appropriate design SCLF data. The design weather conditions adopted for current cooling load calculations seem quite conservative. The use of such criteria could lead to an overestimation of the cooling and hence oversizing of the required air-conditioning equipment.

TABLE 3.8 Typical outdoor design conditions and the building envelope cooling load

Outdoor design conditions	T_{clw} (°C)	T_{clg} (°C)	SCLF (W/m^2)	BECL (W/m^2)
Widely used by local designers (33 °C DB & 28 °C WB)	24.9	9.8	218.3	90.1
Adopted for the Hong Kong Government projects (33.5 °C DB)	25.4	10.3	218.3	91.9
2.5% significance level for summer period (32 °C DB & 26.9 °C WB)	23.9	8.8	218.3	86.5
1% significance level for summer period (32.6 °C DB & 26.9 °C WB)	24.5	9.4	218.3	88.7

3.4 Typical Weather for Building Energy Analysis

The longer the period of weather records are used for peak cooling load and long-term energy estimation, the longer the represented computational time. It is also unfeasible to perform a variant of parametric runs. Therefore, choosing appropriate weather data should be considered depending on the purpose of the building energy simulation (ASHRAE, 1999). For an analysis to check the design performance in a specific year (as in an energy audit), the weather data of the year concerned should be considered. For comparative studies and long-term energy estimation, a yearly representative of the average climatic conditions is often used. Lam et al. (1996) pointed out three types of hourly weather data for building energy simulations:

- Multi-year datasets – these are the fundamental set of weather data and include a substantial amount of information for a number of years.
- Typical years – a typical or reference year is a single year of 8,760 hourly items of data selected to represent the range of weather patterns that would typically be found in a multi-year dataset. Definition of a typical year depends on its satisfying a set of statistical tests concerning the multi-year parent dataset.
- Representative days – these are hourly data for some average days developed to represent the typical climatic conditions. Representative days are economical for small-scale analysis and are often found in simplified simulation and design tools.

For detailed simulation, typical years are most commonly used since analysis using a multi-year dataset is often not feasible and economical for the common design and analysis problems whereas representative days are too limited and not accurate enough. The typical year approach can reduce the computational efforts in simulation and weather data handling by using one year instead of multiple years. Also, a consistent form of weather data is ensured so that results from different studies can be compared. However, there is very little information on developing a typical year for building energy and daylight analysis in terms of monthly and annual energy consumption predictions. This section presents the work on generation of a typical weather year (TWY) using long-term climatic data sets. The reference building with daylight-linked dimming controls was used for the comparative energy studies. The simulation approach was also employed to investigate how close the selected TWY can resemble the long-term weather data in terms of the predicted monthly and annual energy expenditure.

3.4.1 Reference Typical Weather Database

It has been realized that the generation of a representative weather database for the particular site would be more important for the comparative studies on system options and long-term energy prediction. There are several types of typical year which are used in building energy simulations. The test reference year (TRY) is one of the common weather datasets used in Hong Kong (EMSD, 2003). The TRY weather set represents an entire year of actual weather data that includes dry bulb, wet bulb and dew point temperatures, relative humidity, wind direction and speed, atmospheric pressure and cloud cover and type (NCDC, 1976). TRY has its shortcomings. First, no measured solar radiation data is included. Second, the representative year selected for the TRY file takes the data from all of the past years of weather from a process in which the years in the period of record that have months containing extremely high or low mean temperatures were progressively eliminated until only one year remained. The TRY thus reaches a "mild" condition, which may not be considered sufficiently typical to be used as the prevailing "average" weather conditions over a long-term period.

To address the deficiency of the TRY, three other types of weather years were developed, namely the weather year for energy calculation (WYEC), the typical meteorological year (TMY) and the international weather for energy calculations (IWEC). WYEC data represents a weather year, but the method was to select the month whose mean hourly dry bulb temperature was the closet to the 30-year long-term average. If there are unusual or extreme weather patterns, certain days might be substituted. The WYEC followed largely the TRY method but included measured solar radiation data (measured where available or calculated based on cloud cover and type) (Crow, 1981; 1984). TMY contains measured solar radiation data and is constructed from a combination of years. It is considered to be more representative of average weather conditions than the TRY. The TMY method, developed by Sandia National Laboratories in the United States of America (USA) is one of the most widely adopted methods for determining typical weather years (Hall, 1978). A TMY data file consists of twelve typical meteorological months (TMMs) selected from various calendar months in a multi-year weather database. In 1995, version 2 of the TMY weather dataset (TMY2) was developed (Marion and Urban, 1995). The major differences between the TMY and the TMY2 are the periods of records used and the different weighting factors given to climatic variables such as temperature and solar radiation. For instance, TMY used 1948-1975 data, whereas TMY2 uses a new period of records from 1961 to 1990 (Huang, 1998). Also, an index for direct normal solar radiation was added in TMY2. In total, 237 locations of the USA in the TMY2 dataset were completed. Many of the locations of the US in the TMY data set were subsequently updated by the TMY2.

The IWEC weather database also represents a year of weather data which was launched in 1997 using different weighting factors on weather indices compared with TMY and TMY2 (ASHRAE, 2002). The IWEC data files are "typical" weather files suitable for use with building energy simulation programs for 227 sites outside the USA and Canada. In mainland China, nine cities were included in the IWEC weather files. They are Beijing, Gunagzhou, Harbin, Kuming, Lanzhou, Shanghai, Shenyang, Urumqi and the Macau Special Administration Region, but Hong Kong was not included in this exercise. This project detailed the algorithms used to calculate solar irradiance from earth-sun geometry and cloud cover, fill the gaps of missing data and select typical months form the long-term weather data (Thevenard and Brunger, 2002a; 2002b).

It is generally agreed that TMY and WYEC weather datasets tend to perform better than TRY weather dataset in terms of providing users with simulation results that most closely represent typical weather patterns (Crawley, 1998). The TMY method tends to be more widely used in building energy simulations compared with the WYEC method and there has been a number of works on the development of TMYs in the world (Lam et al., 1996; Pissimanis et al., 1988; Said and Kadry, 1994; Zhang et al., 2002). The TMY2 approach is not considered in this study since direct normal solar radiation data has never been recorded by the HKO. In this study, the

TMY and IWEC methods were used to develop TWYs for Hong Kong. Evaluation of the applicability of those TWYs in building an energy simulation program, particularly for buildings with daylighting controls, was adopted.

3.4.2 Basic TWY Selection Procedures

The generation of TWY is based on statistical analysis which evaluates the nine climatic indices, including daily maximum, minimum and mean dry bulb temperatures (DBT) and dew point temperatures (DPT), daily maximum and mean wind speed (WSP) and daily total global solar radiation (GSR). A summary of the nine daily indices and their weighting factors for TMY and IWEC methods is shown in Table 3.9. Selection of each TMM involves minimizing the difference between the month being considered and the long-term distributions. For each TMM, a screening process is first performed to select five candidate years. A non-parametric method, known as Finkelstein-Schafer (*FS*) statistics (Finkelstein and Schafer, 1971) is used to determine the candidates by comparing the yearly cumulative distribution

TABLE 3.9 Weather indices and weighting factors for TMY and IWEC methods

Index		TMY method	IWEC method
Dry bulb temperature	Daily maximum	1/24	5/100
	Daily minimum	1/24	5/100
	Daily mean	2/24	30/100
Dew point temperature	Daily maximum	1/24	2.5/100
	Daily minimum	1/24	2.5/100
	Daily mean	2/24	5/100
Wind speed	Daily maximum	2/24	5/100
	Daily mean	2/24	5/100
Global solar radiation	Daily total	12/24	40/100

function (CDF) with the long-term CDF in the month concerned. An empirical CDF, which is a monotonic increasing function, is defined as follows (Conover, 1980):

$$S_n(x) = \begin{Bmatrix} 0 & \text{for } x < x_{(1)} \\ (k - 0.5)/n & \text{for } x_{(k)} \le x \le x_{(k+1)} \\ 1 & \text{for } x \ge x_{(n)} \end{Bmatrix} \tag{3.5}$$

where $S_n(x)$ = value of the cumulative distribution function at x,

n = total number of elements

and k = rank order number = 1, 2, 3, ……, n -1.

Values of the *FS* statistics are calculated for each of the daily indices using the following equation:

$$\text{FS} = \frac{1}{N}\sum_{i=1}^{N}\delta_i \tag{3.6}$$

where *FS* = value of *FS* test statistics

δ_i = absolute difference between long-term CDF and the yearly CDF at $x_{(i)}$ value and

N = number of daily readings for that month.

A weighting sum average (*WS*) or composite index is then computed for each year, and the five years with the smallest *WS* values are selected as the candidate years for the final selection. The WS value is given by:

$$\text{WS} = \sum_{i=1}^{\text{NI}} \text{WF}_i \times \text{FS}_i \tag{3.7}$$

where *WS* = weighted sum average

NI = number of indices (e.g. 9 for TMY and IWEC)

WF_i = weighting factor for the ith parameter

FS_i = FS test statistics calculated for the *i*th parameter.

The final selection involves two steps. The first step checks the statistics associated with the mean daily DBT and daily total GSR, including the *FS* statistics and the deviations of the monthly mean and median from the long-term mean and median. The second step looks at the persistence in the mean daily DBT and daily total GSR by examining their run structure. Persistence is considered important for the design and analysis of solar systems, since in some cases, the distribution of a given year can be quite close to that of the long term, yet there can still be atypically long runs of cloudy or warm or cool days. The general principle is to select years with small *FS* values, small deviation and typical run structures, but there is no universal procedure or criteria. Various methods for the final selection have been proposed and used by different researchers. Some of them look at the root mean square difference of GSR (Skeiker, 2004), some assess the persistence and the monthly mean and median and some take the year with the lowest *WS* value as the TMM (Yang et al., 2007).

3.4.3 Typical Weather Datasets for Hong Kong

For building designs, weather data that is based on not less than a 30-year period are conservative (Crow, 1981) and typical weather datasets should be periodically reviewed to reflect long-term climate change and variation. The hourly weather records of 27 years (1979 to 2005) were used for TWY selection (HKO, 1979-2005). The required nine weather indices were derived from the hourly measured data. By using Equation 3.7 and the weighting factors listed in Table 3.9, the WS values for all months of the 27-year period were determined. Tables 3.10 and

3.11 present the results for TMY method and IWEC method, respectively. The five candidate years for each month with the lowest values of *WS* are underlined, whereas the lowest one is also displayed in bold. It can be seen that between August and December, the years with the lowest *WS* values are identical. In total, forty-eight out of sixty underlined *WS* values are the same. The statistical results suggest that the month selection using the two approaches often gives similar findings. Accordingly, the 12 calendar months were selected based on the lowest WS values exhibited in the tables.

Figure 3.6 shows the comparisons of the dry bulb temperature CDFs between the long-term and the two TWYs. It can be seen that the variations of the yearly daily mean DBT of the IWEC are closer to the 27-year long-term mean than the TMY. It reveals that the IWEC curve performs better than the TMY curve. The reason is that the weighting factor of daily mean DBT used in the IWEC method is larger than the TMY method. The average DBT of 23.1ºC found in the IWEC format is very close to the long-term value of 23.2 ºC, yet the value of the TMY format is 22.9ºC. Likewise, comparisons of global solar radiation CDFs is shown in Figure 3.7. Again, in general, there is very good agreement between the long-term figures and the two TWYs, which tend to follow the typical "S" shape associated with this type of statistical distribution. The average daily total GSR of TMY and IWEC formats are 13.0 and 12.9MJ/m^2, respectively, which are reasonably close to the long-term average of 12.7MJ/m^2.

TABLE 3.10 Weighted sum averages of the *FS* statistics for each month using the TMY method

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1979	0.131	0.134	0.119	0.059	0.108	0.101	0.185	0.100	0.106	0.337	0.124	0.104
1980	0.067	0.112	0.065	**0.054**	0.100	0.110	0.073	0.089	0.094	0.067	0.136	0.109
1981	0.117	0.102	0.090	0.108	0.102	0.108	0.120	0.093	0.108	0.073	0.123	0.151
1982	0.109	0.109	0.082	0.110	0.088	0.110	0.086	0.066	**0.047**	0.084	0.132	0.079
1983	0.151	0.225	0.199	0.105	0.093	0.095	0.085	0.075	0.094	0.162	0.171	0.081
1984	0.125	0.132	0.090	0.156	0.100	0.088	0.177	0.075	0.077	**0.049**	0.055	0.099
1985	0.084	0.158	0.106	0.100	0.129	0.128	0.114	0.063	0.086	0.067	0.065	0.072
1986	0.175	0.101	0.091	0.055	**0.058**	**0.056**	**0.050**	0.063	0.102	0.067	0.072	0.092
1987	0.113	0.130	0.121	0.068	0.099	0.064	0.078	0.128	0.060	0.072	0.141	0.103
1988	0.127	0.074	0.143	0.108	0.092	0.099	0.094	0.098	0.094	0.098	0.132	0.109
1989	0.095	0.126	0.127	0.091	0.073	0.089	0.066	0.062	0.056	0.066	**0.044**	0.075
1990	0.111	0.075	0.098	0.105	0.102	0.057	0.056	0.110	0.058	0.113	0.083	0.106
1991	0.087	0.093	0.089	0.076	0.095	0.058	0.086	0.062	0.073	0.075	0.078	0.125
1992	0.136	0.106	0.100	0.077	0.111	0.059	0.066	0.087	0.114	0.148	0.146	0.114
1993	0.094	0.136	0.062	0.069	0.061	0.100	0.105	0.055	0.061	0.082	0.107	**0.063**
1994	0.072	0.121	0.100	0.152	0.125	0.110	0.164	0.124	0.132	0.114	0.151	0.195
1995	0.054	0.089	0.079	0.077	0.062	0.090	0.071	0.148	0.064	0.106	0.075	0.109
1996	0.073	0.091	0.051	0.117	0.079	0.096	0.055	0.063	0.053	0.057	0.067	0.070
1997	0.068	0.063	0.095	0.076	0.058	0.106	0.136	0.099	0.115	0.142	0.083	0.141
1998	0.118	0.087	**0.047**	0.127	0.079	0.142	0.087	0.119	0.057	0.058	0.095	0.074
1999	0.053	0.167	0.071	0.112	0.074	0.102	0.120	0.098	0.063	0.074	0.072	0.094
2000	0.063	**0.059**	0.123	0.065	0.072	0.129	0.057	0.085	0.135	0.095	0.104	0.074
2001	0.083	0.113	0.144	0.061	0.085	0.108	0.123	0.084	0.089	0.093	0.106	0.081
2002	0.081	0.144	0.136	0.161	0.093	0.084	0.143	**0.049**	0.077	0.131	0.074	0.122
2003	0.105	0.138	0.055	0.077	0.078	0.119	0.155	0.081	0.057	0.088	0.080	0.146
2004	**0.045**	0.123	0.066	0.075	0.090	0.105	0.099	0.084	0.084	0.164	0.070	0.109
2005	0.062	0.123	0.085	0.085	0.160	0.138	0.082	0.06	0.077	0.087	0.105	0.085

TABLE 3.11 Weighted sum averages of the *FS* statistics for each month using the IWEC method

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1979	0.134	0.147	0.106	0.061	0.130	0.126	0.175	0.117	0.106	0.293	0.119	0.098
1980	0.060	0.134	0.072	0.054	0.119	0.115	0.064	0.094	0.091	0.062	0.128	0.089
1981	0.108	0.101	0.104	0.124	0.093	0.121	0.117	0.105	0.107	0.066	0.132	0.158
1982	0.096	0.098	0.068	0.122	0.086	0.113	0.077	0.061	**0.041**	0.082	0.119	0.089
1983	0.157	0.231	0.208	0.096	0.085	0.100	0.109	0.082	0.116	0.166	0.142	0.082
1984	0.155	0.152	0.095	0.156	0.114	0.085	0.153	0.074	0.080	**0.045**	0.061	0.096
1985	0.097	0.142	0.136	0.125	0.144	0.137	0.117	0.071	0.111	0.070	0.070	0.077
1986	0.155	0.124	0.096	**0.050**	0.055	0.057	0.065	0.074	0.094	0.073	0.096	0.093
1987	0.114	0.147	0.145	0.068	0.106	0.077	0.073	0.127	0.056	0.070	0.127	0.108
1988	0.139	**0.069**	0.160	0.120	0.093	0.109	0.083	0.121	0.096	0.100	0.163	0.110
1989	0.095	0.102	0.109	0.095	0.083	0.086	0.070	0.059	0.066	0.065	**0.051**	0.076
1990	0.103	0.071	0.085	0.112	0.126	**0.048**	0.061	0.139	0.052	0.101	0.074	0.106
1991	0.078	0.097	0.101	0.071	0.107	0.062	0.082	0.053	0.086	0.079	0.093	0.132
1992	0.134	0.120	0.099	0.082	0.13	0.076	0.085	0.108	0.148	0.154	0.154	0.120
1993	0.106	0.148	0.053	0.069	0.057	0.089	0.126	0.055	0.063	0.104	0.093	**0.071**
1994	0.073	0.111	0.103	0.157	0.154	0.097	0.170	0.135	0.133	0.112	0.157	0.193
1995	**0.052**	0.112	0.087	0.077	0.066	0.099	0.092	0.170	0.056	0.11	0.078	0.112
1996	0.093	0.091	0.053	0.133	0.090	0.114	0.069	0.058	0.045	0.072	0.083	0.078
1997	0.060	0.070	0.103	0.085	**0.050**	0.110	0.149	0.091	0.126	0.137	0.104	0.134
1998	0.111	0.081	0.047	0.155	0.092	0.128	0.100	0.150	0.066	0.074	0.117	0.086
1999	0.066	0.184	0.083	0.126	0.081	0.121	0.113	0.088	0.060	0.086	0.072	0.087
2000	0.078	0.076	0.104	0.066	0.063	0.124	**0.049**	0.079	0.137	0.097	0.104	0.080
2001	0.088	0.111	0.149	0.061	0.096	0.104	0.137	0.098	0.088	0.102	0.099	0.076
2002	0.080	0.156	0.167	0.176	0.122	0.099	0.112	**0.053**	0.084	0.112	0.073	0.110
2003	0.102	0.151	**0.046**	0.094	0.096	0.106	0.168	0.073	0.048	0.082	0.071	0.126
2004	0.052	0.127	0.068	0.062	0.083	0.104	0.097	0.073	0.07	0.154	0.078	0.128
2005	0.059	0.101	0.094	0.073	0.156	0.116	0.078	0.071	0.087	0.099	0.107	0.090

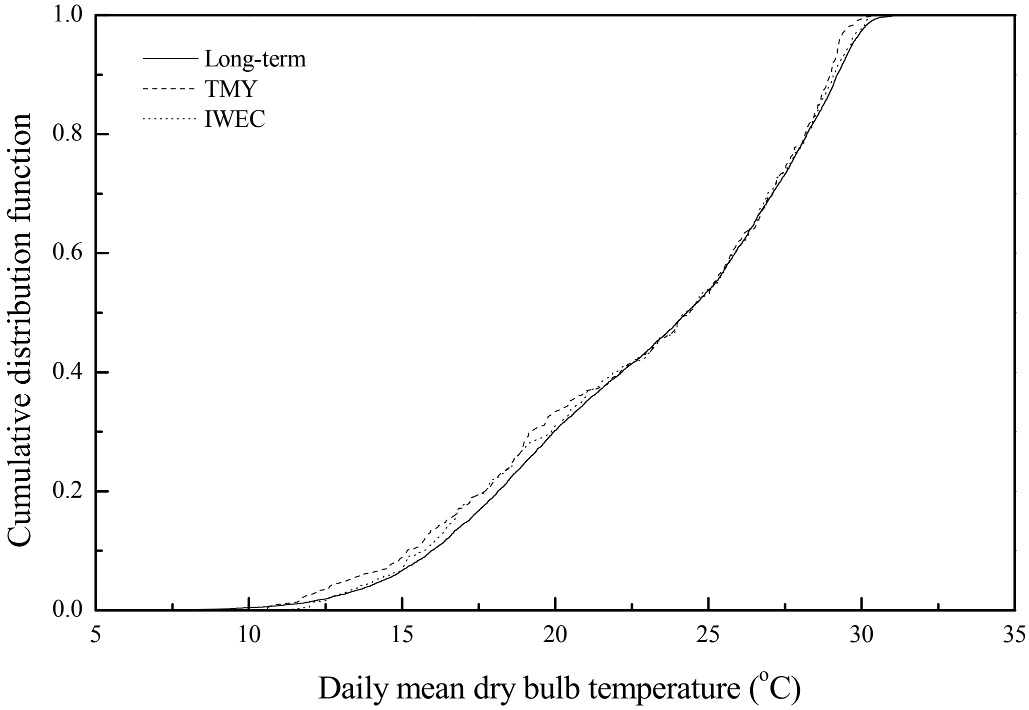


Figure 3.6 Comparing yearly CDF (daily mean DBT) in TMY and IWEC formats with long-term CDF

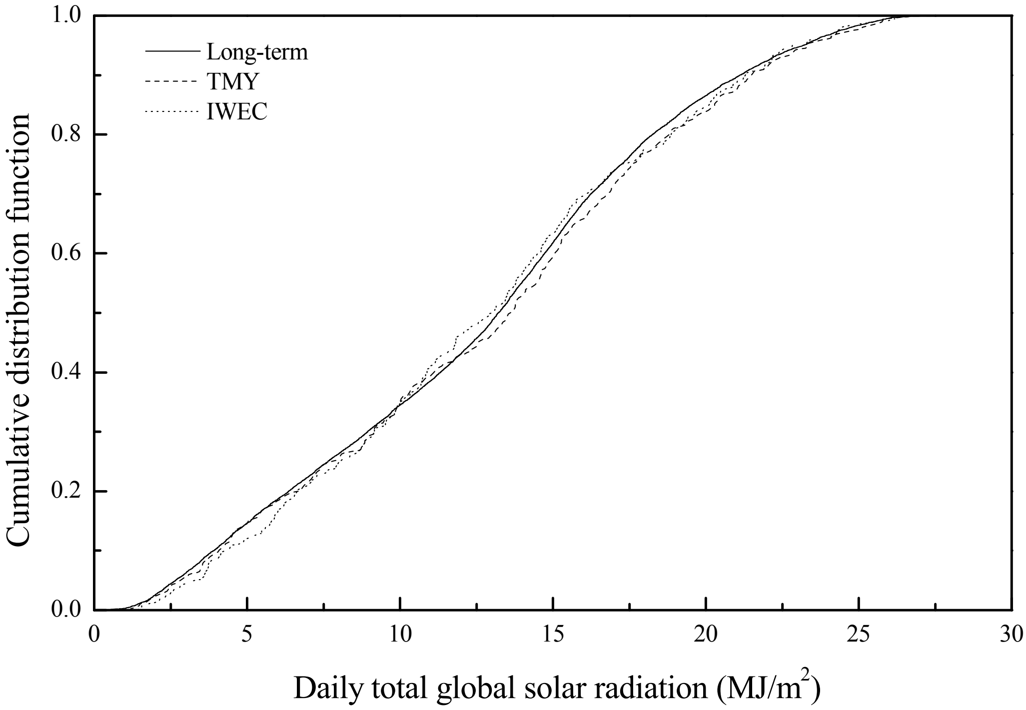


Figure 3.7 Comparing yearly CDF (daily total GSR) in TMY and IWEC formats with long-term CDF

Energy-efficient building and daylighting designs often require the estimation of outdoor illuminance on a horizontal plane. However, there is no measured record available at the HKO. The outdoor global illuminance (E_{vg}) was calculated based on the luminance efficacy model developed by Perez et al. (1990), which is also adopted by the EnergyPlus program for global irradiance to illuminance conversion (LBNL, 2005a). Figure 3.8 shows the comparison of the estimated hourly E_{vg} between TMY and IWEC weather database. The distribution is based on the typical office hours of 08:00 – 18:00 (10-hour working day) in Hong Kong. The figure shows that two CDFs are very close to each other. This implies that similar daylight availability is expected for the two weather databases. It can also be seen that for over 60% of the working year, the outdoor global illuminance exceeds 25klux. Similar results were also reported by Li and Lam (2000b) that for over 60% of the time, daylighting alone can provide an office with 2% daylight factor design with indoor illuminance of 500 lux for all sky conditions.

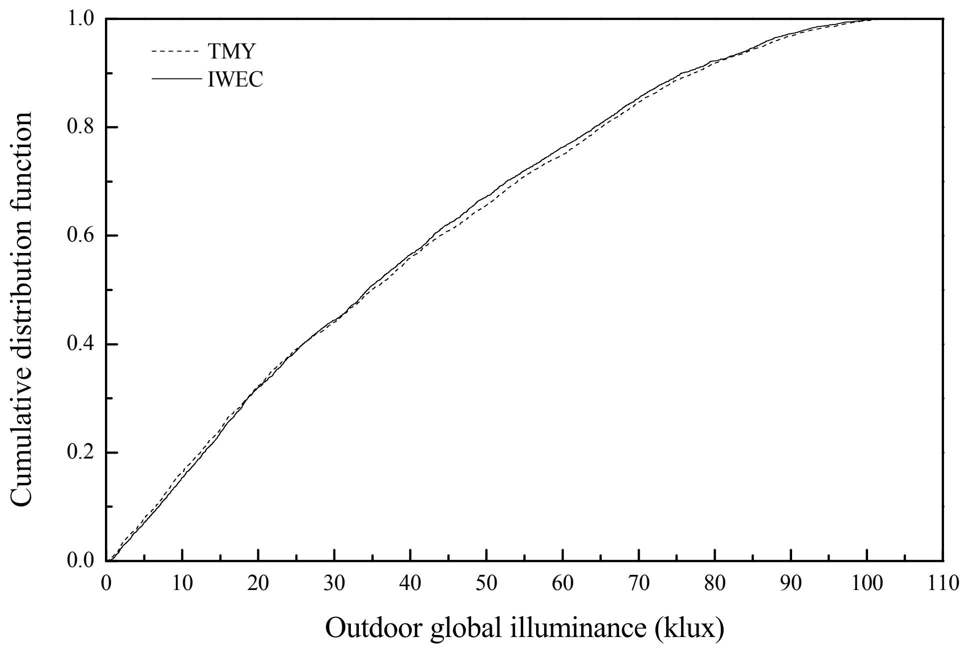


Figure 3.8 Comparing yearly CDF (E_{vg}) between TMY and IWEC formats

The two sets of 12 selected TMMs in TMY and IWEC formats are then used to form weather input files for computer simulations. Apart from the nine weather indices, other weather parameters such as direct normal radiation, diffuse horizontal radiation, atmospheric pressure, wind direction, hours of sunshine and cloud cover were also employed to create the weather files and can be found at the HKO. The direct and diffuse components of solar radiation were determined from their corresponding global solar radiation using the hybrid model established in our previous study (Lam and Li, 1996c). Smoothing of the weather data for discontinuities was carried out using the cubic spline function to avoid abrupt changes at the boundary between two adjacent months from the different years. The last six hours of the preceding day and the first six hours of the following day were adjusted accordingly (Marion and Urban, 1995).

3.4.4 Energy Prediction Test

To get some idea about the effects of weather data from different years and to assess how close the monthly and annual energy consumption predicted from the developed TMY and IWEC weather files are to those predicted from the long-term weather data, a series of simulations was performed. The reference building with daylighting controls was developed to serve as a baseline model for comparison and evaluation. The details of the reference building were described in the section 3.2.1. For daylighting simulation, top-up controls were used for regulating the electric lighting installed at the four perimeter zones in response to the daylight available. Daylight levels were determined at one reference point in each perimeter office at a working plane level of 0.75m above the finished floor level and at a depth of 2.5m centred with respect to the window. A medium reflected and transmitted interior shading device was used to reduce the solar transmittance (T_{sol}), LT by 75 and 60%, respectively, when transmitted direct solar heat gain exceeds 95W/m^2 (Sullivan et al., 1992a; 1992b) or glare index at the daylight reference point exceeds 22 (LBNL, 2005c). It is believed that the shading device can avoid the likely problems of glare, excessive brightness ratios and thermal comfort.

The reference office building with daylighting controls was used to carry out a series of simulations together with different weather files. Three types of weather datasets, namely multi-year (1979 – 2005), TMY and IWEC weather files were simulated. In total, there were 29 simulation runs for the daylighting scheme. Figure 3.9(a) to (c) show the 27 monthly electricity consumption profiles for the individual years from 1979 to 2005. It can be seen that all the years show similar seasonal variations in electricity use. Electricity consumption peaks during the six hot summer months from May to October, when the average outdoor air temperature exceeds 25ºC. The minimum and maximum monthly differences between the twenty seven years are 60 and 112MWh, respectively. These represent 7.9 and 14.8% of the long-term mean monthly electricity use of 758MWh. On an annual basis, the largest difference between the 27 years is 390MWh accounting for 4.3% of the long-term mean annual electricity consumption. Predictions from the TMY and IWEC weather files were analysed and compared with those from the 27 years. Figure 3.10 shows that predictions from the TMY and IWEC weather files lie within the maximum and minimum range of predictions from the twenty seven individual years, and follow quite closely the 27-year long-term mean. It is interesting to note that the electricity consumption in August is larger than that in July when the TMY and IWEC weather

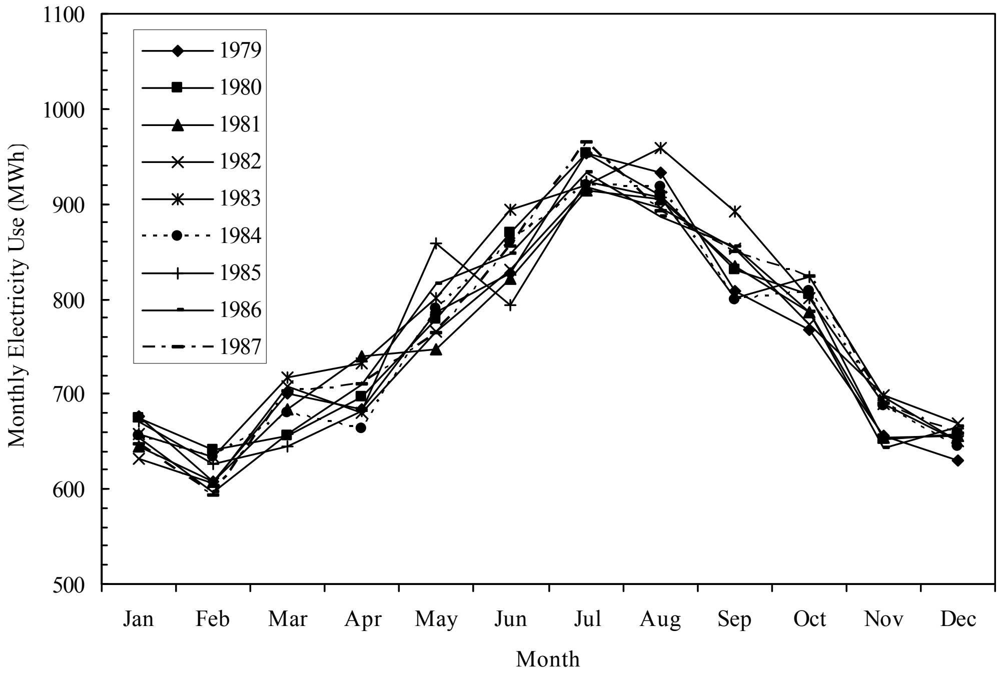


Figure 3.9(a) Predicted monthly electricity use for the base-case building with daylighting control for 1979 to 1987

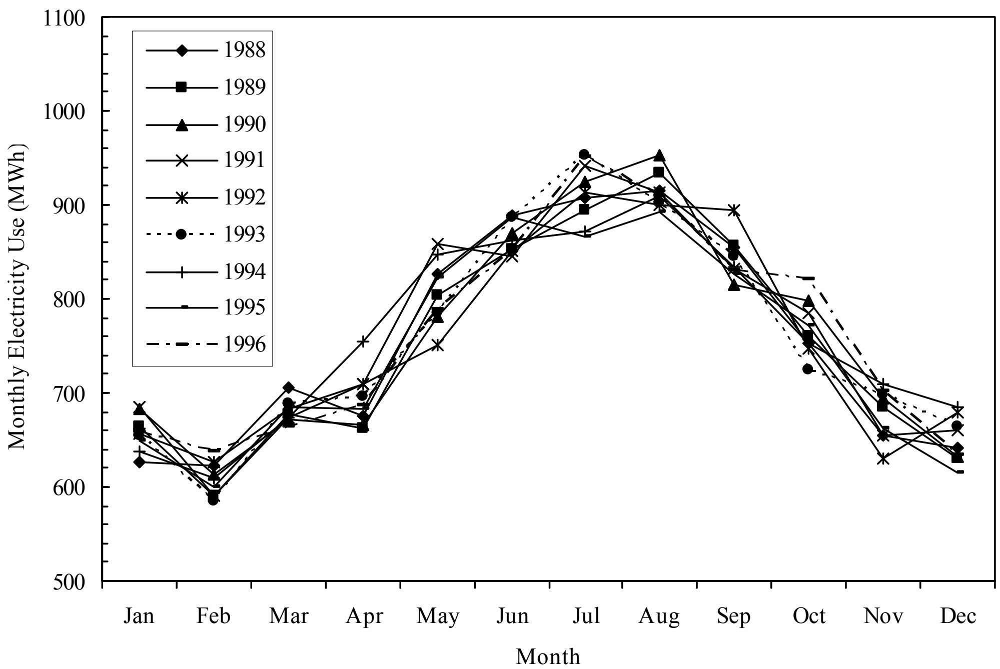


Figure 3.9(b) Predicted monthly electricity use for the base-case building with daylighting control for 1988 to 1996

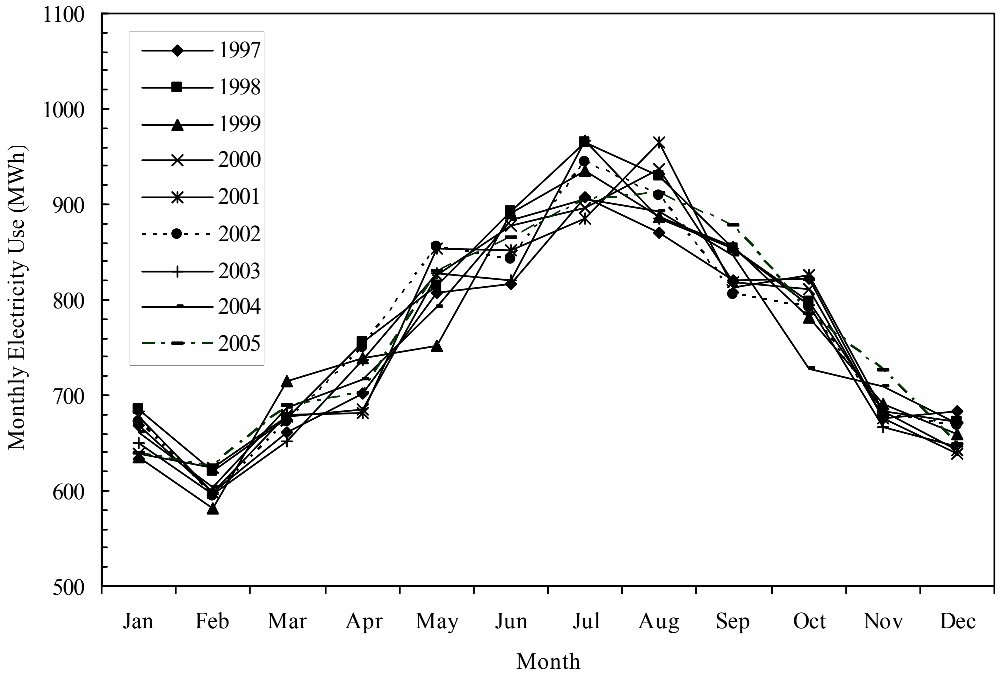


Figure 3.9(c) Predicted monthly electricity use for the base-case building with daylighting control for 1997 to 2005

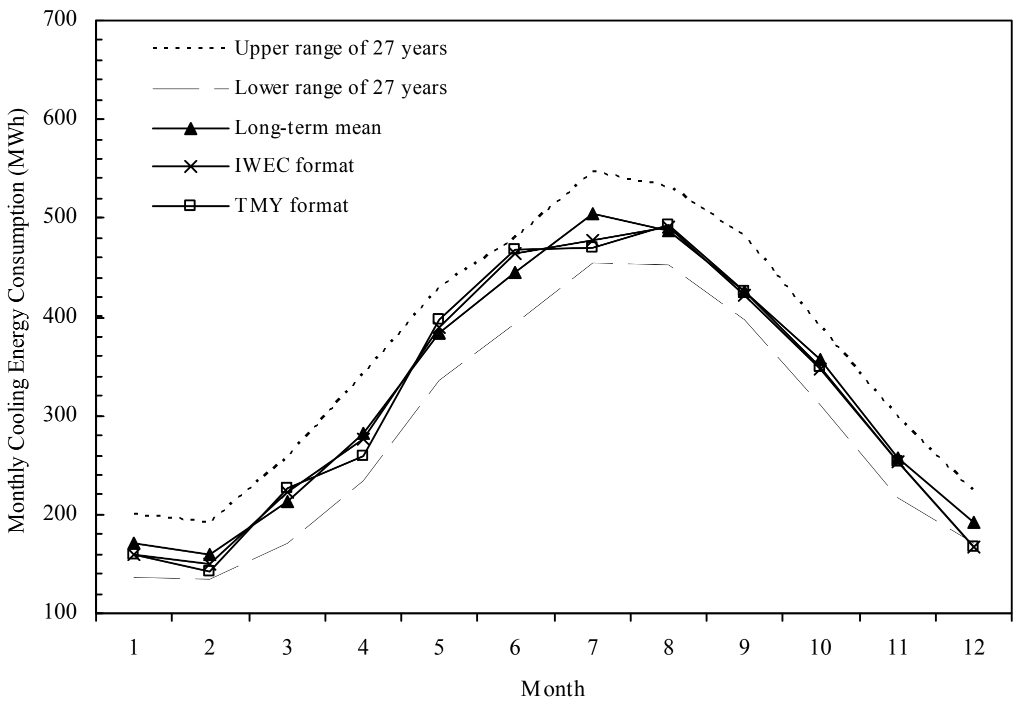


Figure 3.10 Predicted monthly electricity from TMY and IWEC.

files were used for the simulation because the total working days in July are less than those in August under these 2 typical weather datasets. For the long-term mean, July often has the largest electricity use.

To further examine the performance of the typical weather datasets, MBE and RMSE were calculated. Figure 3.11 shows the MBE and RMSE for the twenty seven individual years, TMY and IWEC. It can be seen that MBE ranges from -12.4MWh for 1995 to 20.1MWh for 1998. The year 2000 has the smallest MBE of 0.17MWh and RMSE of 19.4MWh. The MBE for the TMY and IWEC are -4.6 and -5.8MWh, respectively. These represent -0.6 and -0.8% of the long-term average monthly electricity use of 759MWh. The small MBE is a result of a fortuitous cancellation between over and under-estimation. The RMSE is 22.9MWh for TMY. The closest monthly profile is the IWEC which has the smallest RMSE of 19.3MWh,

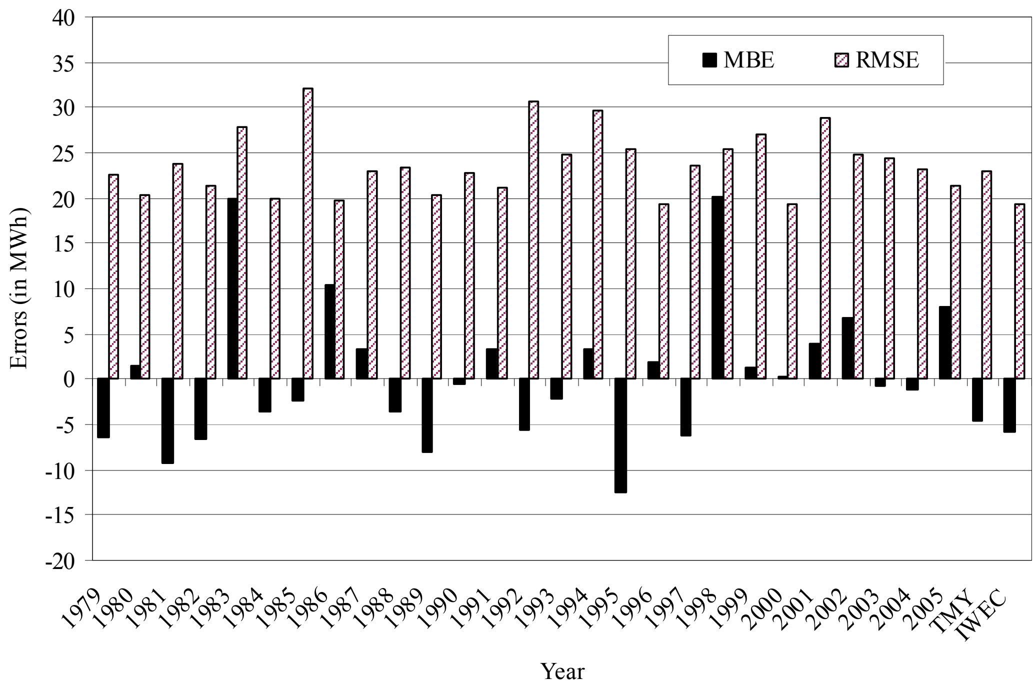


Figure 3.11 Mean-bias errors and root-mean-square errors for the different years, TMY and IWEC

TABLE 3.12 MBE and RMSE (in MWh) for the lighting energy use and cooling requirement using TMY and IWEC methods

	MBE (TMY)	RMSE (TMY)	MBE (IWEC)	RMSE (IWEC)
Lighting energy use	-0.4	3.1	-0.4	3.6
Cooling requirement	-5.7	17.4	-4.8	13.2

accounting for 2.5% of the long-tem monthly mean consumption. The analysis was also carried out for the cooling requirement and lighting energy use. The MBE and RMSE for TMY and IWEC are shown in Table 3.12. The RMSE results are 17.4MWh for TMY and 13.2MWh for IWEC when only the cooling requirement is considered. In terms of percentage, they are more than 4% of the long-term mean monthly cooling energy requirement. For lighting energy use, the variations are small. The RMSE values for both cases are around 3MWh, standing for about 1.5% of the long-term average monthly lighting energy expenditure.

3.5 Summary of Key Findings

To obtain a reliable building energy simulation, accurate prediction of cooling capacity of HVAC plant is required. Hourly cooling load for a developed reference office building has been determined from the computer simulation tool, EnergyPlus, based on 27-year long-term weather databases. It has been found that around one-third of the cooling load is from the building envelope which is weather-dependent. Design values for the three weather variables namely, T_{clw}, T_{clg} and SCLF for building cooling load calculations at different significance levels have been derived from the computer simulation results using multiple regression techniques.

Small mean-bias errors and root-mean-square errors have been obtained, particularly at very low significance levels. Building cooling loads based on the outdoor design conditions commonly used by local building design practices have also been computed and were used for sizing the air-conditioning systems. All the loads are greater than the peak values obtained from the computer simulations. It seems that the current design weather criteria used for cooling load calculation could lead to oversizing of air-conditioning plants. Building designers should, therefore, examine the weather data more closely and choose the appropriate external design conditions according to their applications and acceptable risk levels.

For parametric studies and long-term energy estimation, TWY representative of the prevailing weather conditions is often used. It can greatly reduce the number of computational runs by using one year instead of multiple years (27-year weather dataset). The *FS* statistics technique was used to generate a TMY and an IWEC weather file. It was found that the monthly electricity consumption profile simulated from the TMY and IWEC were in good agreement with the long-term prediction even for buildings with daylighting control. A smaller RMSE for IWEC weather dataset was found. It is envisaged that IWEC can give a comparatively good indication of the prevailing energy performance in building energy simulation in this exercise. The typical weather year in IWEC format is chosen in this research. To have better understanding of daylighting performance and its energy implications for office buildings, detailed energy audits and surveys were conducted for an office. It is also interesting and useful to know more about the use of detailed energy simulation methods to predict more precisely the building energy performance. Therefore, the importance of design parameters for daylighting design should also be discussed. These will be reported in full detail in the following chapter.

Chapter 4 Energy Conservation Design and Sensitivity Analysis of Daylighting

4.1 General

Companies have begun to realise that an efficient use of energy can reduce operating costs and staff are more productive when working in a better indoor environment. Daylight is often considered the best source of light for good colour rendering and closely matches human visual response. The amount of daylight entering a building is mainly through window openings that provide the dual function of admitting light into the indoor spaces and connecting the outside world to the inside of a building. People expect good natural lighting in their working environment. In recent years, there has been an increasing interest in incorporating daylight in architectural and building designs (Atif and Galasiu, 2003; Bodart and De Herde, 2002). Daylighting is recognized as an important and useful strategy in displacing the need for high grade energy (electricity) used for interior lighting (Li and Lam, 2001). Systematic design of daylighting schemes can achieve a better building performance (visual and thermal performance, reduction in peak loads and annual energy consumption). It is not difficult to understand that the utilization of daylight is a design approach with great energy saving potential (Zain-Ahmed et al., 2002).

Daylighting design techniques are often best illustrated through field measurements that form an essential part to provide reliable operational and energy performance data and establish design guidelines (Slater et al., 1996). Empirical data obtained via field measurements, however, help to confirm usefulness, suitability and accuracy (Li and Lam, 2003b). Actual lighting energy expenditure in existing buildings and its characteristics are important information for building owners and operators wishing to develop energy conservation strategies and management programmes (Santamouris et al., 1994). To be familiar with the energy saving potentials due to daylighting controls, a field measurement was conducted for an office using a photoelectric dimming system in February to August 2004. Electric lighting load, indoor illuminance levels, daylight availability and cooling load were systemically recorded. However, field studies have their own limitations, i.e. they are expensive, time-consuming and troublesome to interpret (Wu, 2002). To study long-term energy performance and a wide range of design parameters affecting daylighting analysis of office buildings, a computer simulation technique was employed. This chapter describes the daylighting performance and energy issues for an open plan office via field measurements and studies of the energy performance of certain design variables through computer simulations.

4.2 Daylight and Energy Performance in an Office

With the focus on daylighting and its energy implications in office buildings, a fully air-conditioned open-plan office at the City University of Hong Kong facing northwest (320°) was selected to conduct field measurements in the study. The office is located on the 5th floor of the seven-storey Academic Building with the dimensions of 5.9m (depth) x 10.3m (along the window façade) x 2.4m (height). The monitored room is the working space for the teaching staff members. During normal office hours (i.e. from 9:00 to 17:00), there are around 10 occupants. A total of 14 ceiling-mounted recessed fluorescent luminaries with standard diffusers are installed in four rows parallel to the window facades. A simple photoelectric dimming system is used to monitor the 2 rows of luminaries (6 luminaries) near to the window facade. Each luminaire contains two 36W fluorescent tubes (T5) with a dimmable electronic ballast, which can dim lamp output smoothly and uniformly. The maximum lighting load is 1008W plus the electronic ballast load, given the lighting power density of about 16.7W/m^2 for the interior space. Measurements of the illuminance level due to electric lighting were conducted at night with all the lights on. The mean interior illuminance of the office space was found to be around 480 lux with higher illuminance levels mainly recorded in the working areas. According to the Chartered Institute of Building Services Engineers (CIBSE) Code for Interior Lighting CIBSE, 1987), general offices should have a design illuminance level of 500 lux. This indicates that the existing indoor illuminance level was close to the recommended value. Key features of the office are summarised in Table 4.1.

TABLE 4.1 Brief description of the measured office in the City University of Hong Kong

Location:	5th floor
Main window facing:	North-west (320º)
Floor area:	60.8m²
Dimensions and heights:	5.9 m (depth) x 10.3m (length); ceiling height = 2.4 m; window height = 1.5 m
Constructions of building envelope: (a) External walls (spandrel wall) – 10mm ceramic tiles + 15 mm cement mortar + 200mm concrete + 20mm plastering (U-value = 1.91 W/m²°C) (b) Windows – 6mm tinted single glazing (Solar transmittance = 0.5, Light transmittance = 0.75, U-value = 5.6 W/m²°C)	
Office hour:	Mon. to Fri.: 09:00-18:00; Sat.: 09:00-13:00; Sun. closed
Daylighting control:	First two rows of luminaires from the window glazing; 500 lux at 0.75m above floor; Minimum lighting power = 20% (daylight exceed 500 lux at the reference point)
HVAC design parameters:	Occupancy density = 10 persons Lighting load = 1008 W Equipment load = 40 W/m² Infiltration = 0.6 air change per hour during fans OFF Indoor air temperature = 24 ± 1° C

4.2.1 Dimming System and Measuring Equipment

A simple photoelectric dimming system was installed in the office in February 2004. The electronic circuitry is more energy efficient than conventional ballasts. As indicated in the catalogue, the power required by each electronic ballast is around 1 W. The photosensor mounted onto the luminaire located near the mid-point of the second row was used to measure the light intensity. To have more energy efficient lighting controls, only the six luminaries (two rows) near the window wall were monitored by the dimming system. The sensor detected both the reflected electric light as well as daylight to provide a ‘closed loop’ control. The indoor illuminance on the working plane was measured once per day to ensure that the design illuminance could be maintained. The detected lighting level was sent to the dimmable electronic ballasts to vary the light output of the fluorescent lamps accordingly. For high frequency controls, the lamps cannot be fully dimmed to extinction and residual light output and power consumption will appear. However, such system operation may be less noticeable and less annoying to occupants (Littlefair, 2001b). It was reported that most dimming ballasts could dim lamps to less than 20% of maximum light output (Choi et al., 2005). The daylight illuminance data transmitted via the vertical window glass was recorded by an illuminance meter, which was manufactured and calibrated by Minolta of Japan. The silicon photocell with cosine and colour corrections measure illuminance level up to 300 klux with an accuracy of ±2%. Data-management software namely, T-A30, was used to capture the measured results simultaneously twice per second, averaged over 1 minute. The logged data was sent to a notebook computer for storage. The measured data only gave an indication of the daylight availability for the office, and the sensor itself did not form any part of the dimming control. Information on the amount of daylight available is very useful for daylighting scheme evaluations. The measurement of electric lighting consumption was conducted by means of a power analyzer and its accessories manufactured by Fluke, the Netherlands. A piece of software called FlukeView 41 Windows was used to transmit the data to another notebook computer for storage and subsequent analysis. As indicated in the specifications, the accuracy for power measurement is ±2% + 6 counts (i.e. the range for a real power of 1000W is between 974 and 1026W). Again, the data were averaged over 1-minute interval in order to match the collected daylight illuminance results. The water flow and temperature sensors were connected to the main chilled water pipe for the open-plan office to measure the chilled water flow rate and the supply and return temperatures. The accuracy is ±1.5% for full scale measurement. Data were recorded every 10 minutes which is the normal response time for central air-conditioning systems. The logged data were collected in a desktop computer via a program, called ON-CP Data Logging Software Version 2.0. Figure 4.1 shows the lighting and air-conditioning layout and the arrangement of measuring equipment for the office.

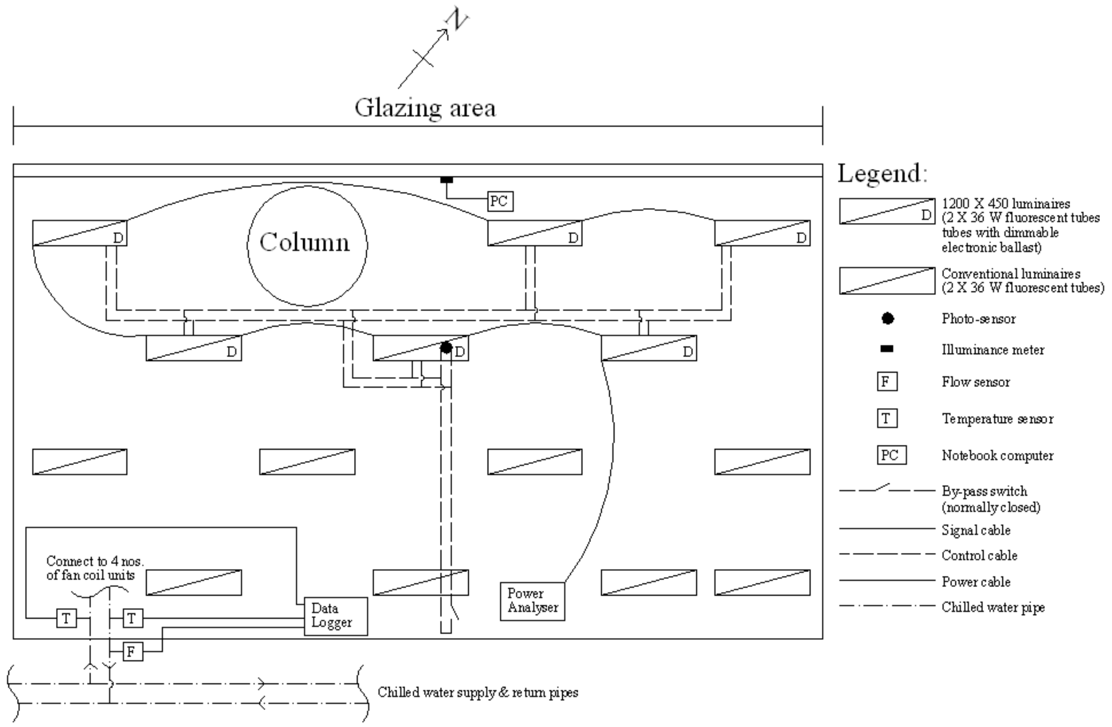


Figure 4.1 Lighting and air-conditioning layout for the office

4.2.2 Electric Lighting Energy Consumption

The illuminance was set at 500 lux to meet the recommended design interior illuminance level. Field measurements including illuminance levels and electric lighting energy expenditure were conducted between February and August 2004. Data were recorded five days (Monday to Friday) per week under normal working hours between 8:00 and 18:00. This 7-month measured data formed the basis for further study and assessment. In any field measurement, it is inevitable that there will be some short periods of missing data due to various reasons. Considerable effort was made to obtain a continuous record of data and in all, about 70,000 readings (1-min data) were made for each parameter.

Electricity use for the six fluorescent luminaries (two rows) in the office under the automatic dimming controls were recorded and analysed. Figure 4.2 presents the average daily electricity consumption profile for the 7 months (i.e. Feb – August) with a 500 lux set-point. The pattern can reflect the monthly variations in daylighting performance. In general, similar electric lighting expenditure for the 7 months are observed. Substantial energy savings occur between 11:00 and 16:00 h when the office space receives large amounts of daylight. Since the office faces northwest, more direct components of high illuminance levels were obtained in the afternoon contributing to less electric energy load in this period. As the daylength increases, decreasing trends in the electric load from February to July can be identified in early morning (8:00-10:00) and in late afternoon (15:00-18:00h). The lowest hourly electric lighting load of 178 Wh appears at 15:00 in June. It is interesting to note that both March and April consume high electric lighting energy. This is not surprising given the unstable weather conditions in spring (Li et al., 2002b).

The area under the lighting load curves indicates the total amount of daily electric lighting energy used. Based on the logged electric lighting energy consumption data during nighttime, the electric lighting load for the two rows of luminaries (i.e. the 12 numbers of fluorescent lamps under dimming controls) without daylighting was estimated to be around 430W. Taking a typical daily dimming system operating time of 10 hours (08:00 – 18:00), the daytime daily lighting energy expenditure was 4.3 kWh for the two rows of light fittings under the dimming system. Compared with the electric lighting load in Figure 4.2, the amount of average daily and monthly energy savings due to the daylight-linked automatic lighting control was obtained and is summarised in TABLE 4.2. The daily savings range from 1.1kWh in March to 1.7kWh in June. It also represented over 30% reduction in electricity use for artificial lighting in the office space under the dimming control in the seven months. Two issues should be pointed out. Firstly, the estimated reduction did not include savings in the air-conditioning which was due to the heat dissipation from the operation of the electric lighting. The likely energy consumption would be further reduced. Secondly, the estimation was based on the existing dimming control system, which monitored only the two rows of luminaries near to the window façade. If the dimming system was applied to the whole open-plan office, the total electric lighting energy savings would be more. However, the amount of energy saving for the lamp fittings in the other two rows would be smaller (Li and Lam, 2001) and the capital cost of dimming equipment may be doubled. The reduction of electric lighting energy saving per luminaire and the increase in initial cost mean a longer payback period. The cost implications need further assessment. It is believed that Figure 4.2 and Table 4.2 can provide a good indication of the likely energy savings for an open-plan office and the findings can be applicable to other internal space with similar architectural designs and electric-lighting patterns.

TABLE 4.2 Daily and monthly electric lighting energy savings

	February	March	April	May	June	July	August
Daily (kWh)	1.3	1.1	1.2	1.5	1.7	1.6	1.4
Monthly (kWh)	27.8	24.5	26.8	33.0	35.4	34.8	30.1

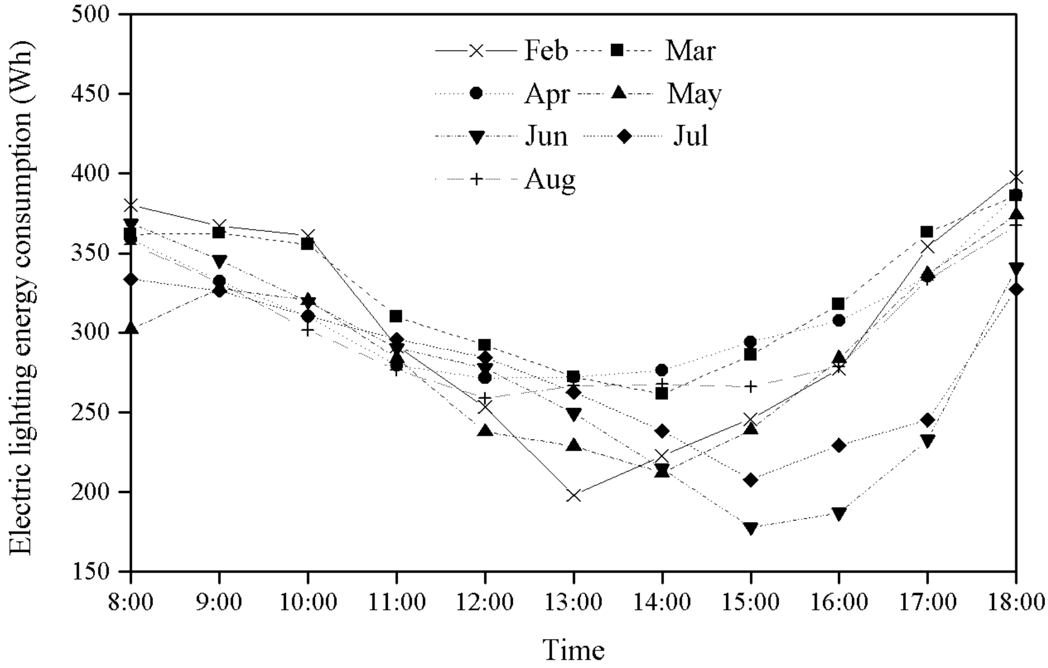


Figure 4.2 Electric lighting energy profile between February and August

The dimmable electronic control gear enables the fluorescent lamps to be dimmed to the required luminous flux. In theory, light output is proportional to the power consumed. However, it has been reported that lamps cannot be dimmed smoothly to total extinction using a high frequency dimming control (Choi et al., 2005; Littlefair, 1998). In normal operation, their residual light output and power consumption will appear throughout the working hours. Graphical representation is a simple and direct approach to interpret such characteristics of the dimming system. The frequency of occurrence for the 10-minute electric lighting load data was analysed for every 10-Wh and the results are shown in Figure 4.3. It can be seen that a marked peak of 15% is observed at a value of 390Wh. The second highest frequency of the power consumption is 400Wh, accounting for 11%. The frequency for the rest of power consumption drops to quite small values, ranging from 0.8% to 6%. A small peak of just over 6% appears when the power consumption is 90Wh or less. These show that under the present dimming control system around 6% of the 7-month period (between February and August), the electric light fittings were dimmed to the minimum value of around 90Wh, and about 30% of the time operated close to full capacity (over 390Wh). For the remaining 64% of the time, the fluorescent lamps were dimmed quite evenly. More dimming time would result when a lower target light level is selected and vice versa. The distribution in Figure 4.3 would depend on a number of factors including the indoor design illuminance, room parameters, location of photosensors and daylight availability. More information should therefore be required to further evaluate the daylight-linked dimming lighting control system.

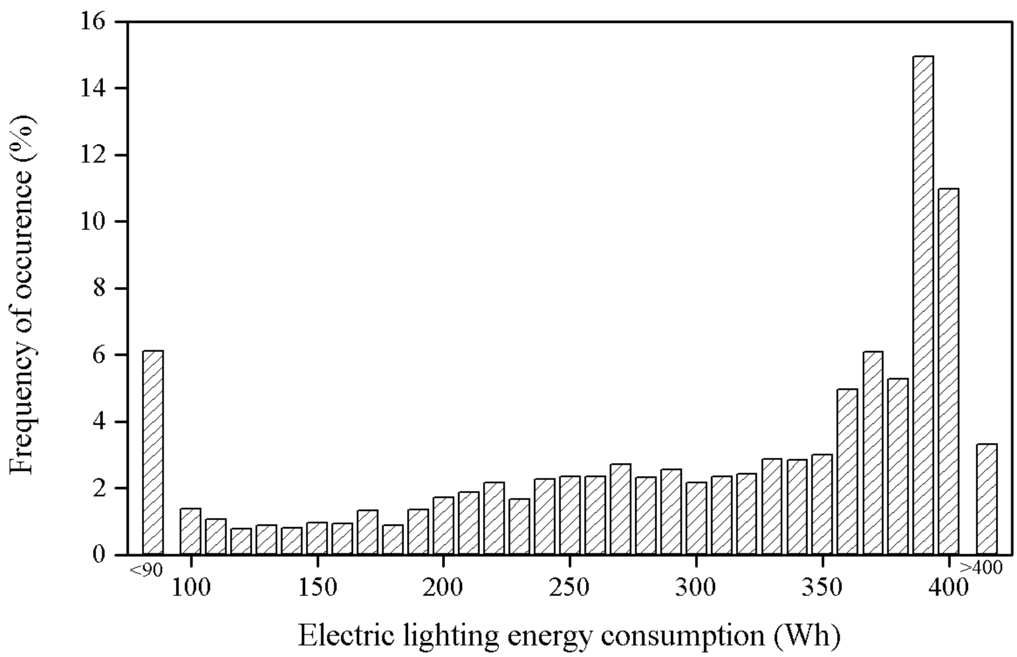


Figure 4.3 Frequency of occurrence for the electric lighting energy consumption

4.2.3 Daylight Availability

The frequency with which a given daylight illuminance occurs provides information on daylight availability (Littlefair, 1990). Since the windows of the fully air-conditioned room were always completely closed, the outdoor vertical illuminance (E_v) cannot be measured directly. Instead, we measured the transmitted vertical daylight illuminance which was the product of the LT of the window and E_v. The 10-minute daylight illuminance data from 08:00 to 18:00 recorded by the illuminance meter was used for the analysis. Figure 4.4 presents the frequency of occurrence of the transmitted daylight availability (LT × E_v) for the office space at an interval of 50 lux. It can be seen that relatively high percentages are recorded at low illuminances indicating that diffuse illuminance is the major component in this region. A small peak appears at about 5,000 lux and the distribution extends widely with a small amount of daylight readings between 15,000 and 43,000 lux. High daylight illuminance values, which correspond to non-overcast sky conditions, are often dominated by the direct sunlight. Since the office faces northwest (320°), these high illuminance data were mainly recorded in the afternoon. Cumulative frequency distribution of the daylight availability for the office space was determined and is shown in Figure 4.5. The cumulative frequency distribution of daylight illuminance can indicate the percentage of the working year in which a given illuminance is exceeded. It can be observed that for a cumulative of 50%, the daylight illuminance level is found around 5,500 lux. This means that for about 50% of the 7-month period (February – August), the recorded daylight illuminance readings are over 5,500 lux. This indicates that the major transmitted daylight availability for the open-plan office would be more than 5,500 lux.

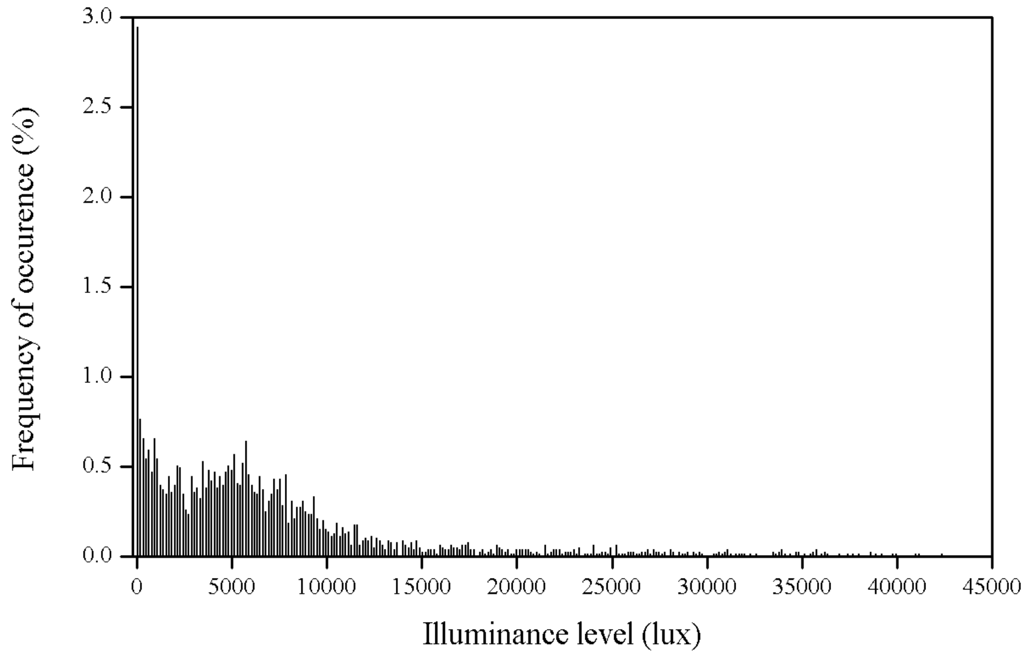


Figure 4.4 Frequency of occurrence for daylight availability

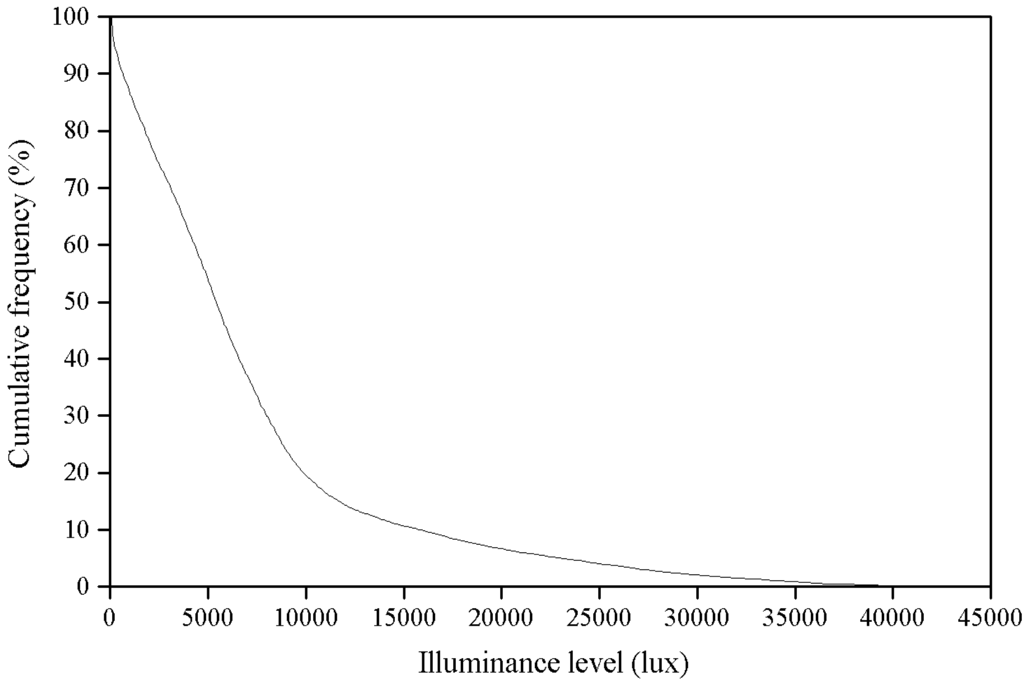


Figure 4.5 Cumulative frequency distribution for daylight availability

The general daylighting performance of an interior space is often assessed in terms of daylight factor (DF), which by definition is the ratio of the internal illuminance to the outdoor illuminance simultaneously available on a horizontal plane from the whole of an unobstructed overcast sky, expressed as a percentage. The standard overcast sky is considered to provide the worst daylighting condition, and consequently under other sky conditions the diversity of daylight will be improved. The DF approach has gained favour owing to it simplicity but it does have two main disadvantages (Littlefair, 1990). First, it is quite difficult to access an unobstructed place. Second, for a side-lit room, the external measurement is influenced by areas of sky that contribute little to the interior measurement. It has been suggested that the E_v could be used to calculate more general factors to account for the orientation of side-lit rooms (Littlefair and Aizlewood, 1996). Again, the transmitted daylight illuminance (LT × E_v) was used to correlate with the illuminance on workplane (E_{in}). The E_{in} and LT × E_v data were logged by means of a multi-point illuminance measurement system with main body adapter (T-A20) and the required receptor head adapter (T-A21) connected serially such that both illuminances were recorded simultaneously. The measurement was carried out on Sunday when all artificial light fittings in the office were off. The sky condition was overcast without any direct sunlight penetrating into the room. The data were collected every minute and averaged over 10-minute intervals. Figure 4.6 shows the plots of LT × E_v and E_{in}. A linear trend between the two sets of data is evident. Through regression analysis, the ratio of E_{in}/(LT × E_v) is found to be 0.0391 with a coefficient of determination (R^2) of 0.977. As R^2 value is of such a high value, it is argued that the workplane illuminance can be predicted using the vertical outdoor illuminance.

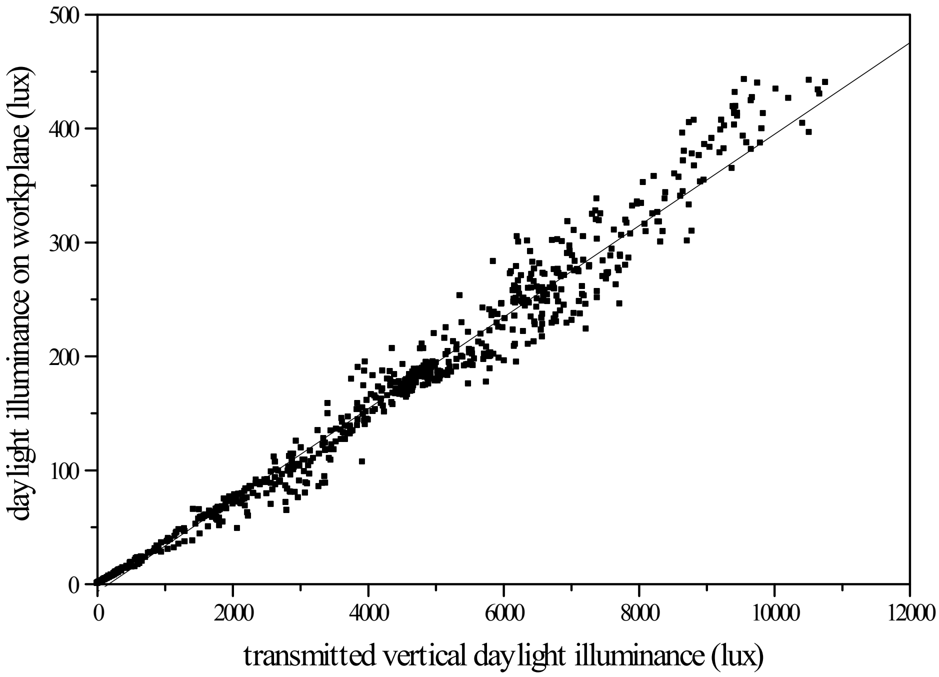


Figure 4.6 The correlation between LT × E_v and E_{in}

4.2.4 Cooling Requirement

The cooling equipment is the major electricity consuming item in commercial development. The water flow and temperature sensors for the cooling energy measurement were set up in March 2004. The chilled water flow rate and temperatures of six months (from March to August 2004) for the open-plan office were recorded and studied. The cooling coil load were then estimated for the office in which the indoor air temperatures of 24±1ºC were maintained in the measuring period. The indoor air temperature was measured once per day to ensure that it could be within the throttling range of the set point. Figure 4.7 shows the daily cooling requirements of the office from March 2004 to August 2004 in which daylighting control was incorporated. The cooling requirement was increased from March of 25kWh to July of 80kWh. The increasing trend is related to the outdoor temperatures and solar radiation. The recorded daily cooling requirements were over

75kWh for June, July and August which were previously identified as the three months with the highest long-term monthly average dry-bulb and wet-bulb temperatures, and global solar radiation in subtropical Hong Kong (Li and Lam, 1999). It is also revealed that the electricity expenditure for cooling are greater than the artificial lighting in office buildings. The annual energy savings due to dimming control systems cannot be determined since year-round measurement was not taken for the office in this study. Therefore, simulation techniques were used to predict the energy expenditure of the office. The input variables of daylighting control, lighting and air-conditioning designs were properly considered and addressed to perform an accurate computational result.

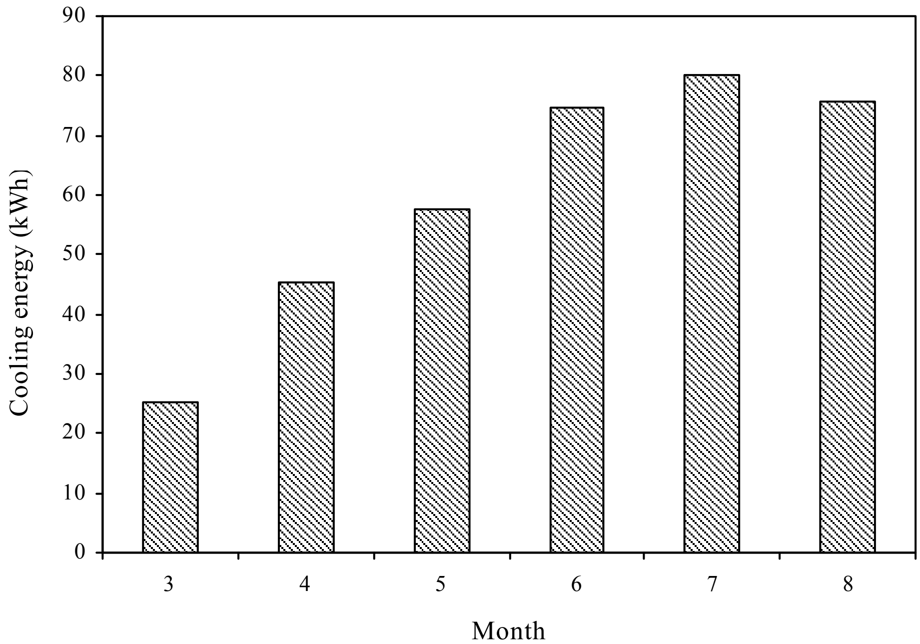


Figure 4.7 Daily cooling energy requirement in different months

4.2.5 Annual Energy Simulation

To have a thorough investigation of the overall effects due to the daylight-linked lighting controls, the building energy program, EnergyPlus, was used to simulate the building energy performance for the open-plan office. Very little work has been done in experimental verification of daylighting control in subtropical regions using EnergyPlus simulation programs. Using the information given in Table 4.1, the computer model was built in accordance with the office configuration, the building materials, and lighting and air-conditioning systems. The year 2004 weather file was used as computer input. In addition, the COP of 2.8, which was the nominal COP of air-cooled chillers for the building was adopted to estimate the cooling electricity expenditure. The simulated results were then compared to the measured results to investigate the accuracy of EnergyPlus.

Figure 4.8 presents the plots of field-measured and computer-simulated lighting energy consumption between March and August 2004. It can be observed that the simulated data are reasonably close to the measured values. In some cases, the predicted and measured values almost overlap. A detailed examination of the figures revealed that lighting energy expenditure was saved substantially in the afternoon (particular between 2 and 3 pm) in most of the months. Likewise, the simulated and measured cooling requirements were analyzed. The simulated and measured cooling requirements between March and August were computed and are displayed in Figure 4.9. The daily cooling load in the measuring period show good agreement between computed and measured profiles. The peak differences of 477kWh, respectively for July are observed. This represents only about 5.7% of the corresponding measured value. Similar performances were found for other months. To further examine the performance of the program, MBE and RMSE were employed. Table 4.3 summarizes the MBE and RMSE for the lighting energy expenditure and cooling load requirements in different months. For lighting energy consumption, the MBE values range from an underestimation of 5.3% in August to an overestimation of 0.9% in March. The reason for these discrepancies is that internal and external obstructions cannot be modelled easily. The RMSE can be just more than 6.7% appearing in July. Referring to the cooling requirements, the MBE and RMSE vary from -0.1% to 3.5% and from 2.3% to 4.7%, respectively. The statistical results indicate that building energy use can be simulated with reasonable accuracy.

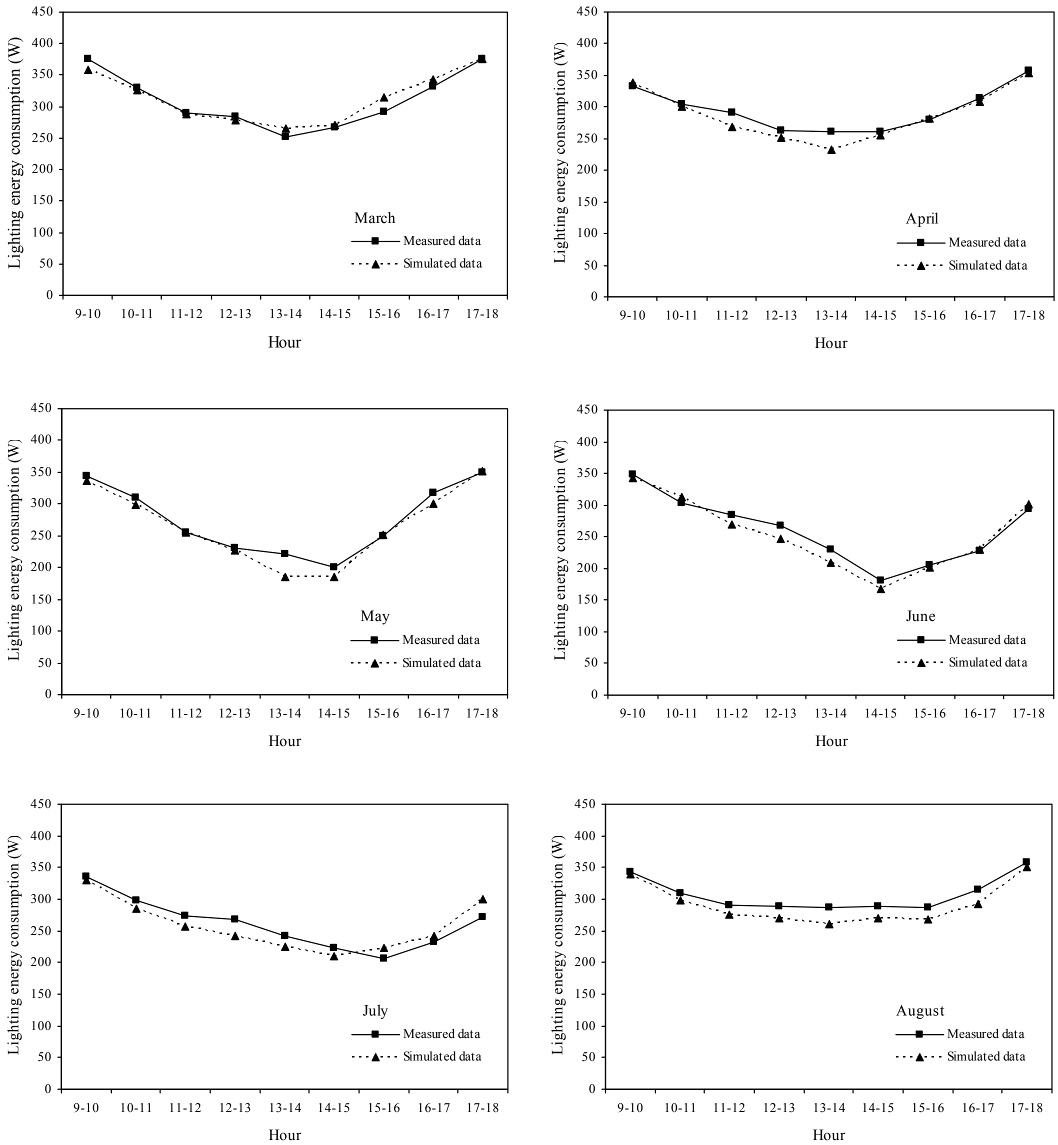


Figure 4.8 The field-measured and computer-simulated lighting energy consumption in different months

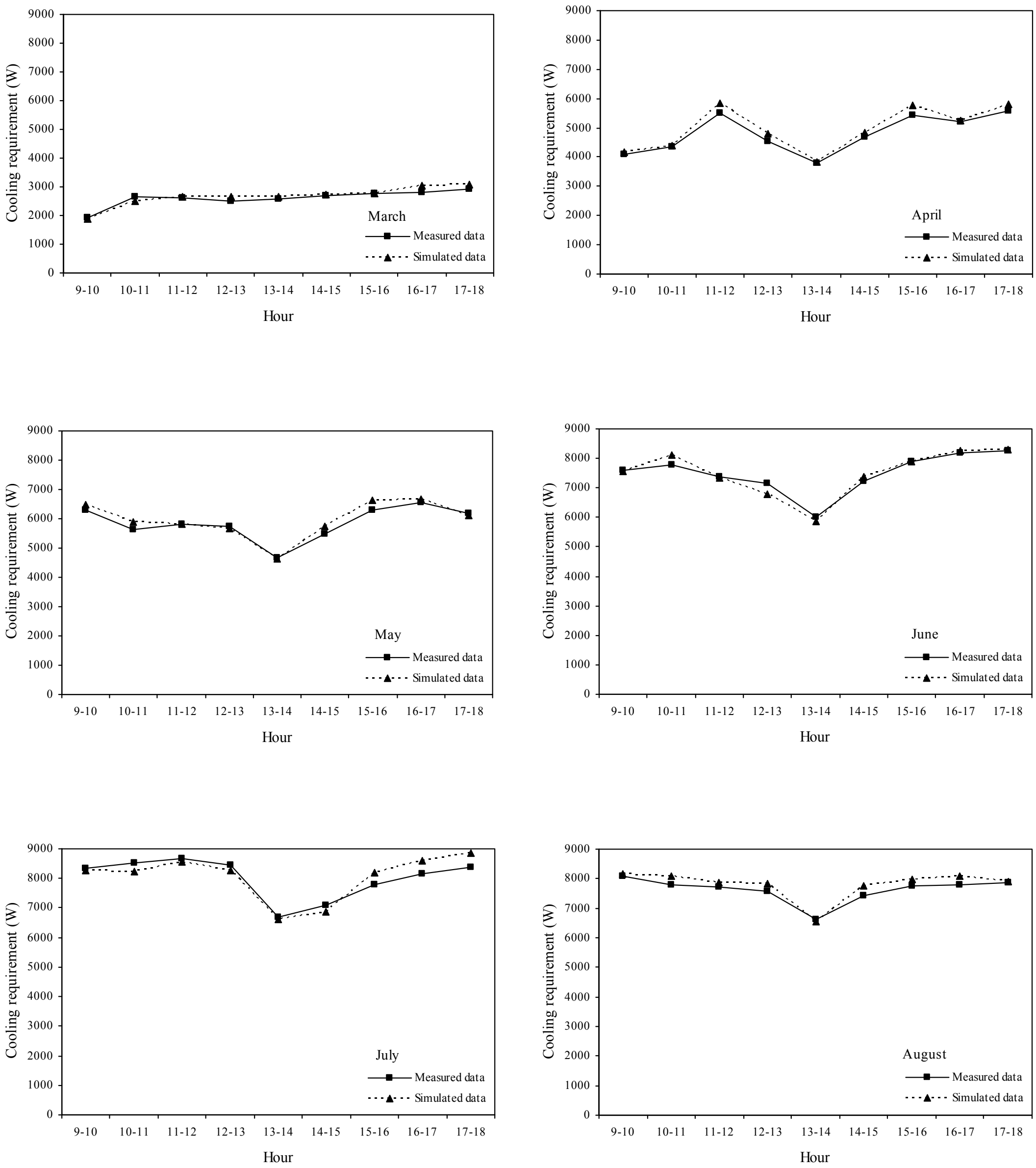


Figure 4.9 The field-measured and computer-simulated cooling energy consumption in different months

TABLE 4.3 Summary of MBE and RMSE for simulated lighting energy consumption and cooling requirement for March to August

		Mar	Apr	May	Jun	Jul	Aug
Lighting	MBE (%)	0.9	-2.8	-3.4	-2.4	-1.6	-5.3
	RMSE (%)	3.7	4.5	5.4	4.8	6.7	5.7
Cooling	MBE (%)	2.1	3.5	1.7	-0.1	0.6	2.4
	RMSE (%)	4.7	4.4	3.1	2.3	3.6	2.9

To demonstrate energy performance of daylighting design, the annual energy expenditure due to lighting and cooling requirements for the open-plan office together with a high frequency dimming control were further simulated based on the same settings. Figure 4.10 illustrates the results using the weather data in 2004. With the daylight-linked dimming control, the annual lighting energy for the two rows of the light fittings dropped from 1139kWh to 800kWh, representing a 30% reduction. As less sensible heat gains were generated by artificial light fittings, the annual cooling energy consumption lowered from 4329kWh to 4157kWh, accounting for a 4% drop. The findings indicate that daylighting designs can result in a certain amount of energy savings in air-conditioned office buildings in Hong Kong.

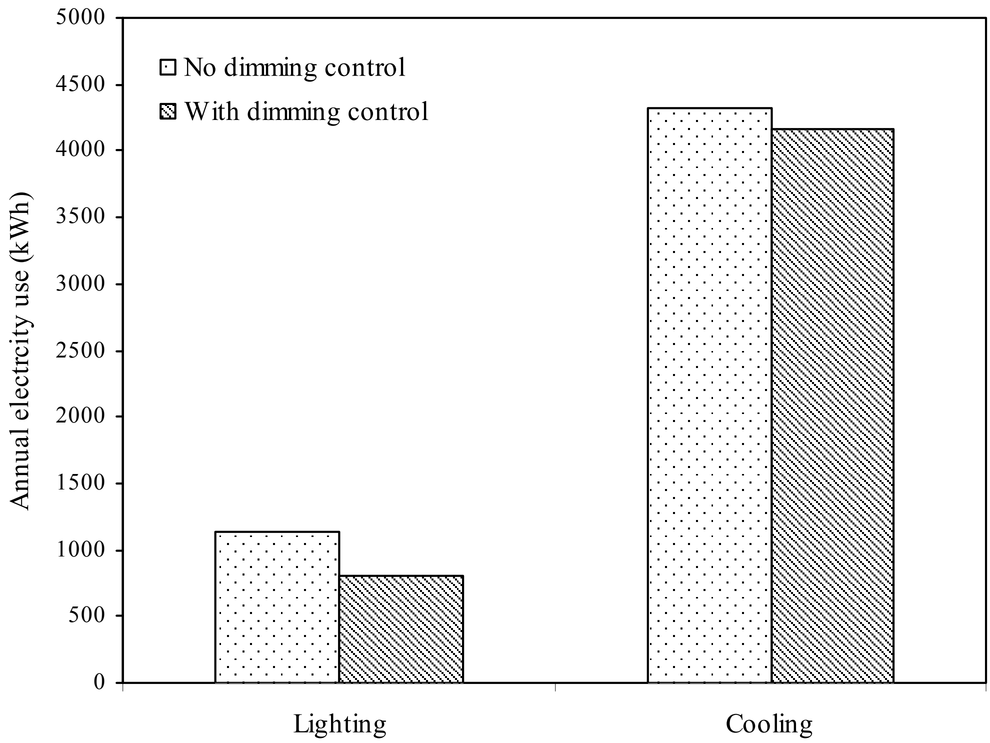


Figure 4.10 The computer-simulated annual lighting and cooling energy consumption for the open-plan office

4.3 Sensitivity Analysis

The validation demonstrated that a computer simulation approach can be used to predict lighting and cooling energy performance with a high degree of accuracy under daylighting controls. Study of the parameters affecting energy and daylighting performance of office buildings is essential for a more systematic and comprehensive building design scheme. With the advancement of computer technology for detailed building energy simulations, these important parameters can be examined extensively. For building and daylighting analysis, energy variations from certain input factors may be more substantial than others, indicating that such variables should be paid particular attention in terms of technical and economic points of view during the design process (Lam and Hui, 1996a). Sensitivity analysis is to compare quantitatively the changes in output with respect to the changes in input. Once the relationships of the input and output parameters of the system are understood, all relevant variables can be appropriately designed to achieve the best building energy performance. Investigations of building energy performance based on sensitivity analysis have been conducted by a number of researchers (Corson, 1992; Gustafsson, 1998; Mottillo, 2001; Tavares and Martins, 2007). Chan (2003) pointed out that high sensitivity elements should be designed with care in order to optimise system performance. However, very little work on sensitivity analysis of parameters relating to daylighting designs has been done. Hui (1996) pointed out that there is no fast rule to cover the entire sensitivity analysis. Instead, the choice of the objective function and the procedure of the analysis were governed by the nature of the problem.

4.3.1 The Principle of Modelling System

Sensitivity can be considered as an input-output analysis of a simulation system. The target of performing sensitivity analysis is to understand the relationships between the input and output parameters of the system such that the designers can select high sensitivity elements and arrange schedules to achieve optimum building energy performance. To measure the sensitivity of a system, the term influence coefficient (*IC*), which is defined by the partial derivates of output (*OP*) and input (*IP*), has been used for thermal systems and building energy simulation (Spilter et al., 1989). Mathematically, it can be given as follows:

$$IC = \frac{\text{change in output}}{\text{change in input}} = \frac{\partial OP}{\partial IP} \approx \frac{\Delta OP}{\Delta IP} \tag{4.1}$$

If only one step change is used to calculate the sensitivity, Equation 4.1 can be expressed by two sets of data as follows:

$$IC = \frac{\Delta OP}{\Delta IP} = \frac{OP_1 - OP_2}{IP_1 - IP_2} \tag{4.2}$$

where OP_1 and OP_2 are the output results and IP_1 and IP_2 are the corresponding input values.

It has been pointed out if more simulation runs are generated in the analysis, *IC* can be obtained from the slope of the linear regression line for the data. For a non-linear correlation, the sensitivity will vary from point to point and *IC* may be computed on the basis of any number of the simulation results. In this study, three different forms for the *IC* were considered and they are shown in Table 4.4. Form 1 is given as Equations 4.1 and 4.2. The *IC* of the second form is defined as the ratio

TABLE 4.4 Different forms of sensitivity coefficient

Form	Formulae	Dimensions
1	$\dfrac{\Delta OP}{\Delta IP}$	with dimension
2	$\dfrac{\Delta OP \div OP_{BC}}{\Delta IP \div IP_{BC}}$	$\dfrac{\%\ OP \text{ change}}{\%\ IP \text{ change}}$
3a	$\dfrac{\Delta OP \div \left(\dfrac{OP_1 + OP_2}{2}\right)}{\Delta IP \div \left(\dfrac{IP_1 + IP_2}{2}\right)}$	$\dfrac{\%\ OP \text{ change}}{\%\ IP \text{ change}}$
3b	$\left(\dfrac{\Delta OP}{\Delta IP}\right) \div \left(\dfrac{\overline{OP}}{\overline{IP}}\right)$	$\dfrac{\%\ OP \text{ change}}{\%\ IP \text{ change}}$

a. ΔOP, ΔIP = changes in output and input respectively.
OP_{BC}, IP_{BC} = base case values of output and input respectively.
IP_1, IP_2 = two values of input.
OP_1, OP_2 = two values of the corresponding output.
$\overline{OP}, \overline{IP}$ = mean values of output and input respectively.

b. For the form (3b), the slope of the linear regression line divided by the ratio of the mean output and mean input values will be taken for determining the sensitivity coefficient

of differential output divided by the base-case model output result to the differential input divided by the base-case model input value. Form 3 is similar to Form 2 but with the differential input and output variables divided by their corresponding mean values, instead of the base-case data. Form 1 is the simplest expression which is often used in comparative energy studies as the coefficients obtained can be used directly for error evaluation. Forms 2 and 3 have the merit that the *IC*s are dimensionless values expressed as a percentage. Form 3a only applies to one-step change (i.e. non-linear cases) and Form 3b is applicable to multiple sets of data (i.e. linear cases). Generally, Form 3 can use the original input and output data according to the actual situations without reference to the base-case mode. When the input of the base-case is zero, the *IC* cannot be computed using the Form 2. Whichever form is employed, the forms of *IC*s should be clearly indicated to avoid confusion and misunderstanding particularly when they are presented in a dimensionless ratio.

4.3.2 The Input Parameters and the Outputs

To work out the influence coefficient of a modelling system, the building inputs to EnergyPlus should be examined. Analysis of the simulation results of the reference office building with and without daylighting controls was carried out for sensitivity analysis in this study. Apart from the building inputs, another important factor in building simulation is the external weather data. The IWEC weather database was found to be representative of the prevailing weather conditions in Hong Kong and it was selected in this comparative study for all the building energy simulations. Lam and Hui (1996) stressed that correct interpretation of simulation outputs was important for obtaining meaningful sensitivity analysis. Since we were interested in knowing how changes in the building designs (i.e. input parameters) would affect the energy performance of the building, the annual building energy consumption (in MWh) and the peak electrical demands (in kW) were adopted as the output parameters in the sensitivity analysis and subsequent computation of the influence coefficient in this study.

The simulated annual electricity consumption without daylighting controls is 10GWh. On a per unit gross floor area basis, this represents an energy use index (EUI) of 204 kWh/m^2, which is quite close to the previous findings for office buildings (Lam et al., 2000; 2004). The annual building electricity consumption was broken down into six items, namely, electric lighting, office equipment, space heating, space cooling (including heat rejection), pumps and fans. The breakdown of these components was analyzed for the reference case with and without daylighting controls and is shown in Figure 4.11. It can be seen that energy demands related to HVAC systems are the most important components. Air-conditioning energy requirements, namely, space cooling, pumps and fans dominate the total energy expenditure, contributing over 41% total energy use. This indicates the overwhelming importance of air-conditioning in cooling-dominated commercial buildings in Hong Kong. As expected for the subtropical climate in Hong Kong where the winter is short and mild, relatively insignificant building energy of about 3% is consumed for space heating. The internal electric loads (lighting and equipment), which are non-weather-dependent, account for 56% of the total building consumption. The computed results show that air-conditioning and artificial lighting represent over 75% of the total building electricity consumption, indicating the importance of lighting and solar heat gain in air-conditioned office buildings in subtropical climates. With daylighting control, annual electricity consumption is lowered from 10 to 9.0GWh. The EUI is 181kWh/m^2, representing a 10% reduction. The annual lighting energy is significantly decreased by around 890MWh, which is about 26% of the total building electric lighting use and corresponds to 8.9% of total building energy expenditure. The finding also represents a smaller but noticeable reduction in cooling energy and heat rejection resulting from less sensible heat gains generated by artificial lighting fittings. There is a slight increase in space heating, due mainly to a small drop in heat dissipation from electric lighting during the short heating season. The energy use for office equipment remains unchanged. Fans consume less amounts of electricity because of the lower peak load and hence smaller plant sizes.

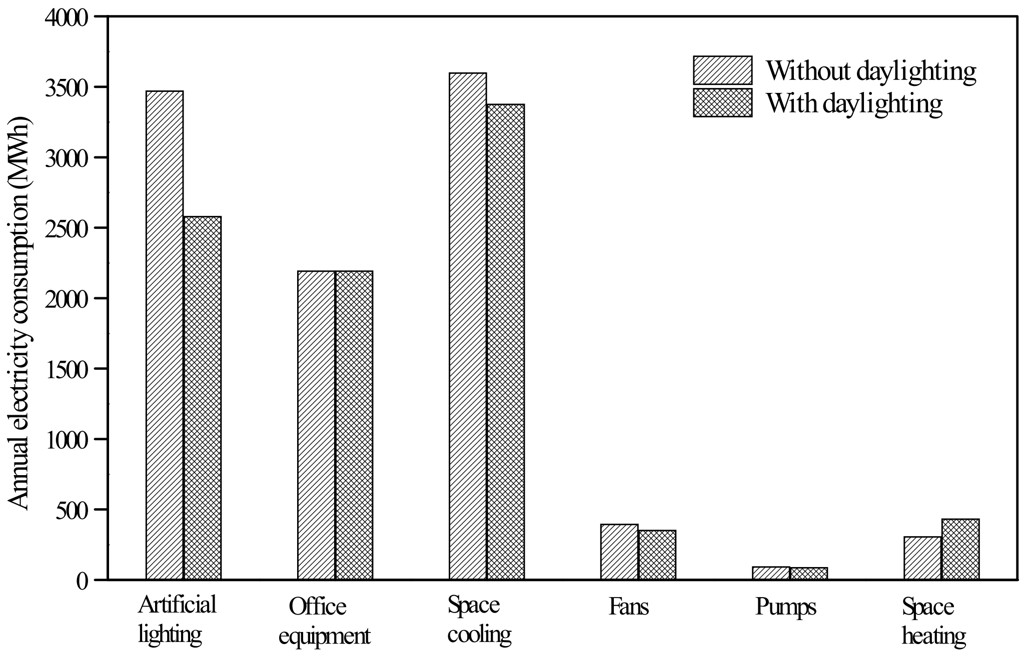


Figure 4.11 Breakdown of annual electricity consumption for the reference office building with and without daylighting controls

Peak electricity demand determines the maximum loads and is useful for plant and equipment sizing. Initial costs and operating strategies are affected by the maximum demands, even though building energy consumption may not be significantly affected. The peak electricity loads occur exactly the same time (i.e. 16:00 for without daylighting and 17:00 for with daylighting) and date (15^{th} August for without daylighting and for with daylighting) as the peak cooling plant demands. This is not surprising, given that air-conditioning represents over 50% of the total electricity use in cooling-dominated office buildings. The electrical demands of electric lighting, office equipment, space cooling, pumps and fans (space heating is not required in hot summers) are shown in Figure 4.12. It can be seen that the energy demands related to air-conditioning energy requirements (space cooling, pumps and fans) are the most important components. When daylighting is not considered, peak electricity consumption is 4552kW. Air-conditioning energy requirements dominate the total energy consumption, contributing about 67% to peak total energy expenditure. The internal electric loads (lighting and equipment), which are non-weather-dependent, account for 33% of total building consumption. When daylighting controls are in operation, the peak electricity use is lowered by 11% to 4048kW. Electric lighting load is significantly reduced by 219kW, which is over 28% of the total building electric lighting load and corresponds to 4.8% of the total building energy use. The figure also indicates smaller but noticeable air-conditioning load reduction resulting from less sensible heat gains generated by artificial light fittings. The electricity use by the HVAC system is decreased from 3103 to 2817kW. The energy demands for equipment remain unchanged. The results also show that air-conditioning and lighting represents over 80% of the total building electricity load, indicating that proper daylighting design is a key area for making substantial peak load reductions in cooling-dominated office buildings in subtropical climates.

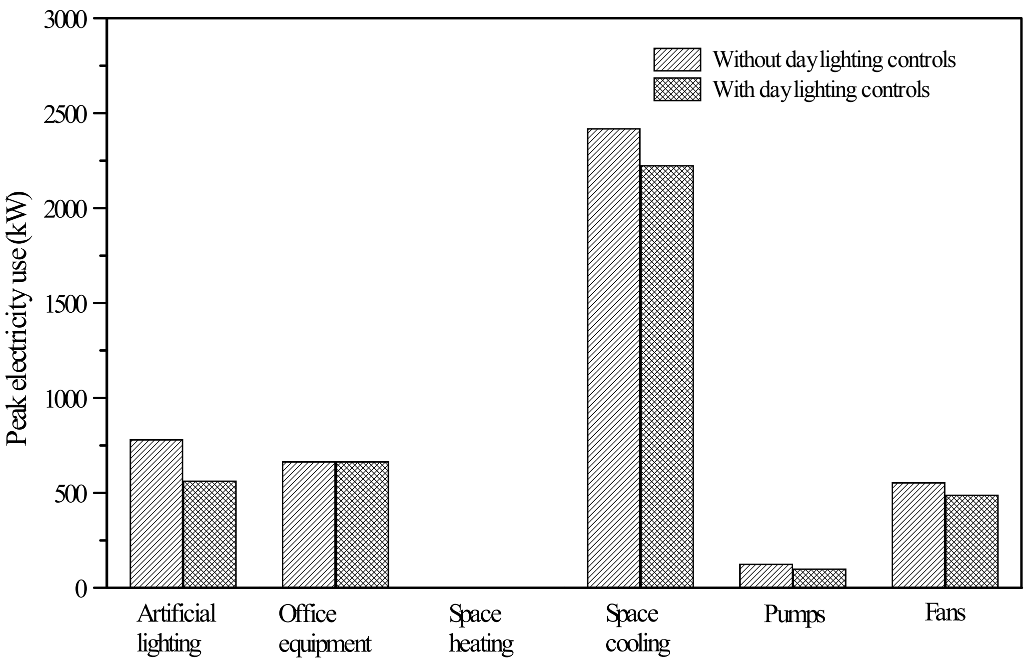


Figure 4.12 Breakdown of peak electricity consumption for the reference office building with and without daylighting

4.3.3 Influence Coefficient Determination

Careful selection of input parameters and correct interpretations of simulation output are important for obtaining meaningful results. The output results for the study are annual building energy expenditure and peak design loads. To work out the *IC* of a modelling system, the building design criteria for the simulation tools should be examined. In this study, a total of eight design parameters relating to daylighting scheme were selected for sensitivity analysis and they are shown as follows:

- Window-to-wall ratio (WWR),
- Light transmittance of windows (LT),
- Projection ratio of overhang (OV),
- Projection ratio of side-fins (SF),
- Reflectance of internal ceiling (R_c), floor (R_f) and wall surfaces (R_w),
- Ratio of height of external obstruction to the separation (H/L). It was assumed that four obstructing blocks of the same building width as the base-case building were located in front of the base-case building at the four cardinal orientations (N, E, S and W).

After determining the design variables to be studied, perturbations were introduced by changing systematically a range of different values to each of the input parameters, one at a time. The aim of the parametric analysis was to assess the influence of each input parameter to the output results, enabling the important and critical characteristics or the influence of the input parameters to be identified. Table 4.5 shows the base-case values and perturbations for the eight input parameters.

TABLE 4.5 Summary of base-case values and perturbations with and without daylighting controls

Abb.	Input parameter	Base case value	Perturbation nos.	Min. value	Max. value
WWR	Window to wall ratio	0.43	21	0	0.8
LT	Light transmittance of windows	0.3	19	0	0.8
OV	Projection ratio of overhang	0	19	0	0.8
SF	Projection ratio of side-fins	0	19	0	0.8
R_c	Reflectance of ceiling	0.8	17	0.1	0.8
R_f	Reflectance of floor	0.2	17	0.1	0.8
R_w	Reflectance of wall	0.5	17	0.1	0.8
H/L	Height of obstructing building/separation	0	15	0	10.5

The total building electricity consumption which is an indicator of the whole building energy performance is often the most significant factor of interest to building energy analysis. Peak electricity demand determines the maximum loads and is useful for equipment sizing. Initial costs and operating strategies are influenced by the maximum demands, even though building energy consumption may not be significantly affected. Previous studies (Lam et al., 2002a; 2005) revealed that daylight admitted through the building envelope offers an opportunity to substantially reduce the total electricity a building uses and the peak building electricity load. To better understand such electricity reductions, the output results are presented in two terms, namely the incremental electricity use (IEU) (i.e. the difference in electricity expenditure between buildings with and without daylighting controls for the same input parameters) and incremental peak electricity use (IPEU) (i.e. the difference in the peak electricity load between buildings with and without daylighting controls for the same input parameters). As daylighting is an energy saver, the IEU and IPEU would always be expressed in negative values.

For Annual Electricity Use

Correlations between the IEU and the eight input parameters including the internal reflectance for various internal surfaces, external obstructions and building envelope design variables were calculated and are shown in Figures 4.13 – 4.16. It can be seen from Figure 4.13 that IEU varies almost linearly with the OV, SF, R_c, R_f and R_w when the input projection ratio and the reflectance are up to around 0.8. As the projection ratio increases, the amounts of IEU for both OV and SN reduce indicating less electricity savings. Reverse trends for the R_c, R_f and $R_{w.}$ are observed when the reflectance rises. This shows that there are more electricity reductions with higher reflectance values. Figure 4.14 presents the correlation between IEU and the LT. As the LT increases initially from zero, there is an abrupt reduction in lighting energy, representing the high capacity of daylight to replace artificial lighting. However, as LT continues to increase, daylighting does not significantly contribute to additional lighting energy savings but degrades progressively and very small additional energy savings are found beyond 0.3 LT. Figure 4.15 displays the correlation between IEU and WWR. With the use of daylighting controls, increasing WWR means that more daylight is admitted and utilized. However, changes in WWR also increase the building envelope cooling load. At first, with small WWRs, artificial lighting is substantially displaced by daylight. With more glazing areas, the capability of daylight to substitute electric lighting is reduced gradually. When the illuminance from daylight exceeds the required level, no further lighting energy will be saved. A diminishing return for the IEU at a WWR of about 0.35 is observed and the IEU starts rising (i.e. less building energy savings) when the WWR is 0.4. Figure 4.16 plots IEU against H/L (i.e. the same external obstruction height for the four cardinal orientations). It can be seen that the peak IEU is 1040MWh when there is no external obstruction. As H/L increases initially, there is a certain decrease in electricity savings, indicating that the capacity of daylight to replace artificial lighting and reduction in heat dissipation from the electric lighting installation are high. However, as H/L continues to rise, daylighting does not significantly contribute to additional building energy savings but debases progressively. There are very small additional energy savings when H/L is beyond 7 (i.e. the obstructing building blocks are higher than the reference generic building).

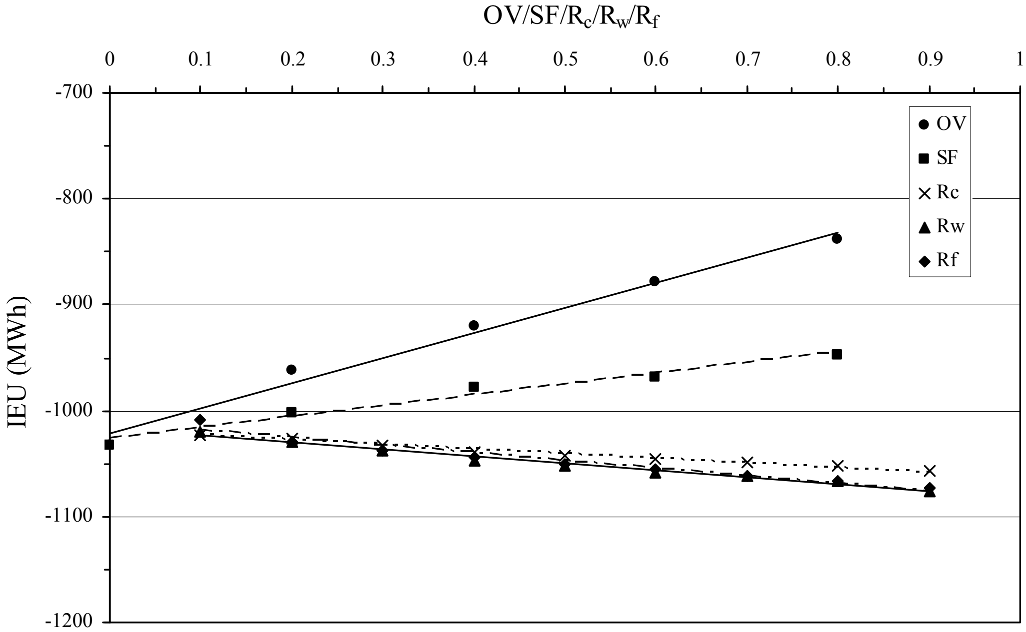


Figure 4.13 The correlations between incremental electricity use (IEU) and overhang (OV), side-fin (SF), and reflectance of ceiling (R_c), floor (R_f) and wall surfaces (R_w)

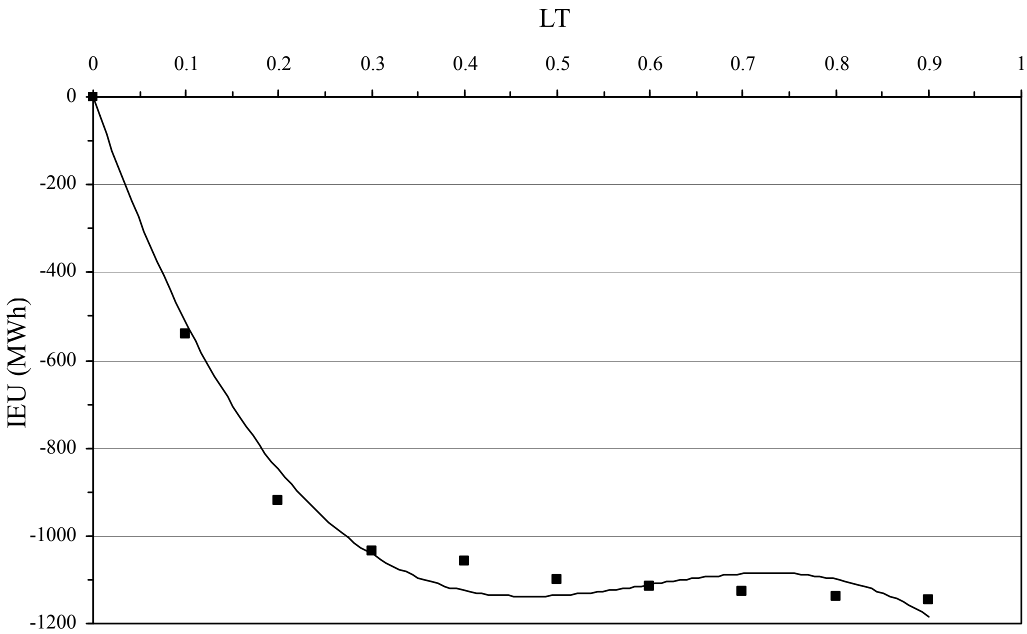


Figure 4.14 The correlation between incremental electricity use (IEU) and light transmittance (LT)

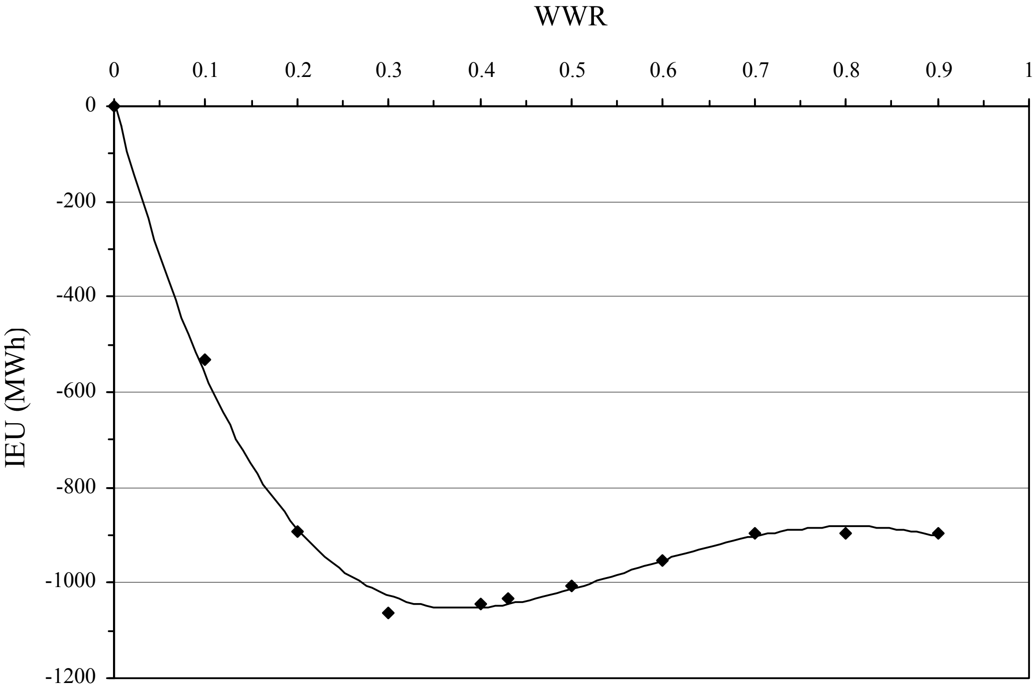


Figure 4.15 The correlation between incremental electricity use (IEU) and window-to-wall ratio (WWR)

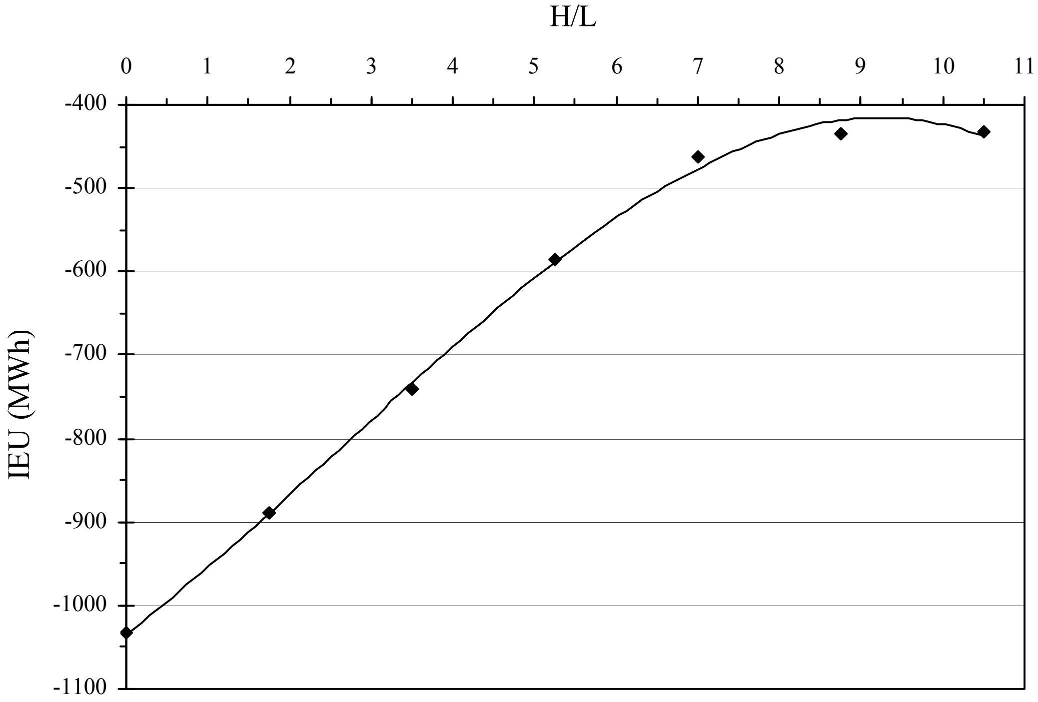


Figure 4.16 The correlation between incremental electricity use (IEU) and the ratio of height of external obstruction to separation (H/L)

The input-output characteristics of the annual IEU can be studied by looking at the sensitivity coefficients. The forms of sensitivity coefficient as mentioned in Table 4.4 were computed and Table 4.6 summarizes the sensitivity coefficients of the annual building energy consumption for the eight input parameters. The sensitivity for individual parameters is indicated by the absolute quantity of the coefficients. The negative and positive sensitivity coefficients shown in Form 1 denote respectively, less and more building energy expenditure with respect to the corresponding input parameter changes. With different physical meanings, for each range of any input parameters, a positive sensitivity coefficient in Form 1 and negative values in Forms 2 and 3 were determined and vice versa. The results show that energy performance of daylighting is highly influenced by building envelope design and external obstructions, such as WWR, LT and H/L, in which higher *IC*s in either Form 1 or 3 were found compared with the others.

TABLE 4.6 Sensitivity coefficients for design parameters in incremental electricity use (IEU)

Abb.	Range	Sensitivity coefficients for IEU (MWh)			
		Form (1) (MWh per input unit)	Form (2) (% *OP* per % *IP*)	Form (3a) (% *OP* per % *IP*)	Form (3b) (% *OP* per % *IP*)
WWR	0.0 – 0.1	-5327	2.216	1.000	
	0.1 – 0.2	-3587	1.492	0.756	
	0.2 – 0.3	-1714	0.713	0.439	
	0.3 – 0.4	204	-0.085	-0.068	
	0.4 – 0.43	89	-0.123	-0.118	
	0.43 – 0.5	291	-0.173	-0.189	
	0.5 – 0.6	499	-0.207	-0.280	
	0.6 – 0.7	573	-0.238	-0.402	
	0.7 – 0.8	12	-0.005	-0.010	
	0.8 – 0.9	12	-0.005	-0.011	
LT	0.0 – 0.1	-5417	1.572	1.000	
	0.1 – 0.2	-3789	1.100	0.777	
	0.2 – 0.3	-1129	0.328	0.289	
	0.3 – 0.4	-256	0.074	0.086	
	0.4 – 0.5	-409	0.119	0.171	
	0.5 – 0.6	-171	0.050	0.085	
	0.6 – 0.7	-94	0.027	0.054	
	0.7 – 0.8	-118	0.034	0.078	
	0.8 – 0.9	-83	0.024	0.062	
OV	0 – 0.8	244			-0.105
SF	0 – 0.8	103			-0.042
R_c	0.1 – 0.9	-42	0.012		0.020
R_w	0.1 – 0.9	-72	0.021		0.034
R_f	0.1 – 0.9	-80	0.015		0.038
H/L	0 – 1.75	83	-	-0.075	
	1.75 – 3.5	85	-	-0.273	
	3.5 – 5.25	88	-	-0.581	
	5.25 – 7	71	-	-0.829	
	7 – 8.75	16	-	-0.275	
	8.75 – 10.5	1	-	-0.023	

For Peak Electrical Demand

Likewise, correlations between the IPEU and the same eight input parameters were determined. Similar patterns as those presented in Figures 4.14 – 4.16 were obtained but with different output values and units. Two critical envelope design parameters, LT and WWR, which contribute higher energy saving potential are illustrated in Figures 4.17 and 4.18. The curves were fit by cubic equations and R^2 values were more than 0.97 indicating a strong correlation between the IPEU and the two design parameters. Again, the sensitivity coefficients for the peak electrical demands were worked out and are given in Table 4.7. By comparing the *IC* in Table 4.7 with those in Table 4.6, it can be observed that the sensitivity values of the parameters for peak electricity demand have similar features to those for the annual building energy consumption. By examining the hourly values of individual load components in detail, it is noticed that not all the load components peak and coincide at the same time and by the same hour. Most of them tend to peak in the summer months and the peak time of the building is often dictated by the external weather conditions and internal cooling requirements. If there are some extremities in the weather data file, they are unlikely to be reflected in the peak design loads. This can be a good indicator for the selection and assessment of typical weather conditions for such building energy simulation studies. When the objective and decision criteria of the building designs are more on the initial costs of the systems, the peak design loads should be a priority area for analysis.

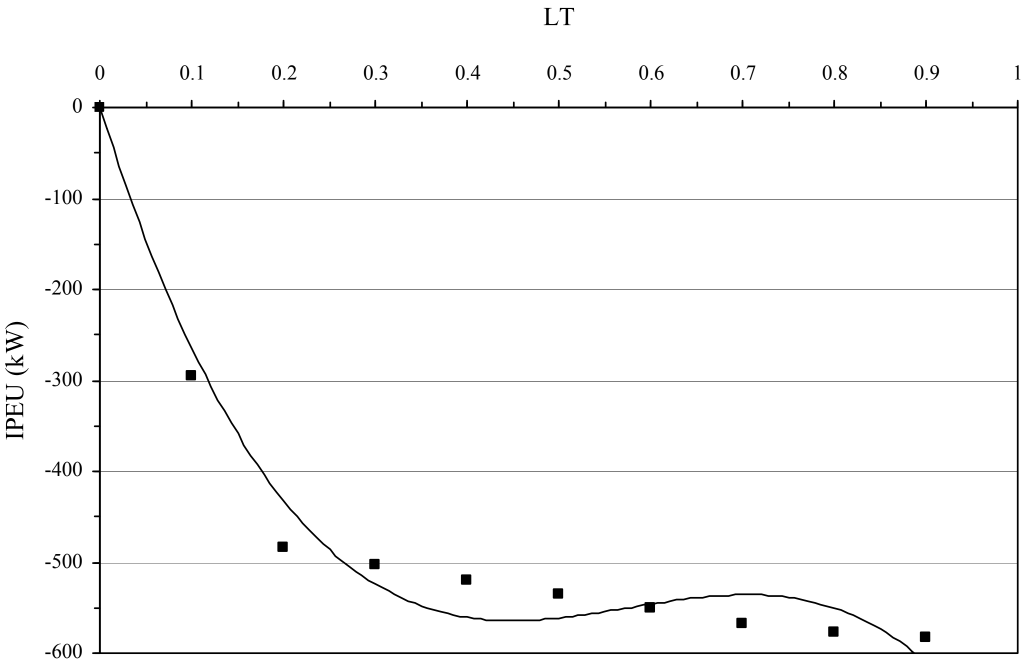


Figure 4.17 The correlation between incremental peak electricity use (IPEU) and light transmittance (LT)

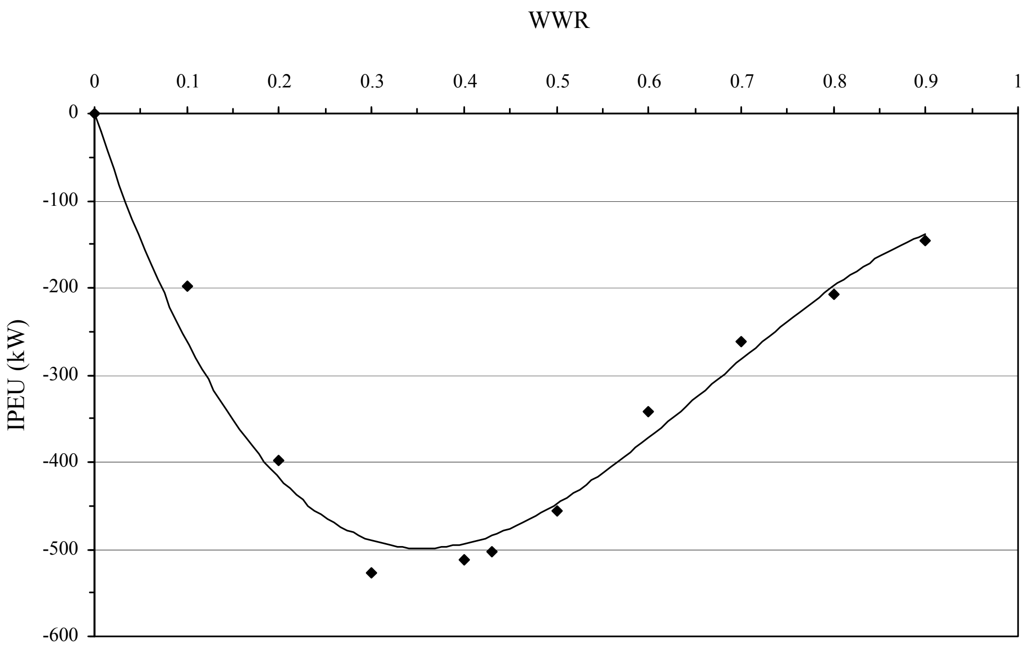


Figure 4.18 The correlation between incremental electricity use (IEU) and window-to-wall ratio (WWR)

TABLE 4.7 Sensitivity coefficients for design parameters in incremental peak electricity use (IPEU)

Abb.	Range	Sensitivity coefficients IPEU (kW)			
		Form (1) (kW per input unit)	Form (2) (% *OP* per % *IP*)	Form (3a) (% *OP* per % *IP*)	Form (3b) (% *OP* per % *IP*)
WWR	0.0 – 0.1	-1974	1.686	1.000	
	0.1 – 0.2	-2012	1.718	1.012	
	0.2 – 0.3	-1277	1.090	0.690	
	0.3 – 0.4	147	-0.125	-0.099	
	0.4 – 0.43	80	-0.228	-0.218	
	0.43 – 0.5	481	-0.586	-0.666	
	0.5 – 0.6	1131	-0.966	-1.559	
	0.6 – 0.7	813	-0.694	-1.751	
	0.7 – 0.8	544	-0.465	-1.744	
	0.8 – 0.9	612	-0.522	-2.951	
LT	0.0 – 0.1	-2948	1.756	1.000	
	0.1 – 0.2	-1897	1.130	0.730	
	0.2 – 0.3	-191	0.114	0.096	
	0.3 – 0.4	-156	0.093	0.107	
	0.4 – 0.5	-156	0.093	0.133	
	0.5 – 0.6	-156	0.093	0.158	
	0.6 – 0.7	-181	0.108	0.211	
	0.7 – 0.8	-78	0.047	0.103	
	0.8 – 0.9	-68	0.041	0.100	
OV	0 – 0.8	220			-0.213
SF	0 – 0.8	55			-0.046
R_c	0.1 – 0.9	-78	0.046		0.075
R_w	0.1 – 0.9	-70	0.042		0.068
R_f	0.1 – 0.9	-70	0.028		0.068
H/L	0 – 1.75	17		-0.031	
	1.75 – 3.5	25		-0.143	
	3.5 – 5.25	31		-0.340	
	5.25 – 7	36		-0.639	
	7 – 8.75	25		-0.685	
	8.75 – 10.5	3		-0.105	

4.3.4 Regression Models

The basic objective of regression models is to build an equation correlating a dependent variable to independent variables. Regression techniques have been used for studying the effects of various parameters on building energy performance (Lam et la., 1997) and developing simplified equations for daylighting analysis (Huang et al., 1989). By varying the input variables for the base-case reference building, a number of simulations are run to generate data for deriving algebraic expressions (Chou et al., 1993). With understanding developed from the previous sensitivity analysis, a regression method is conducted for the individual design parameters study to identify the principal forms of relationships. Simple linear or polynomial regressions are applied to study the simulation results for each parameter at a time. Regression techniques using the statistics package SPSS (Norusis, 2005) were employed for the single regression analyses. The statistical methods use the least-square approach to find the best fit to the data. The 'goodness of fit' of the model is measured by the coefficient of determination (R^2), which is equal to unity if a perfect fit is found. The standard error, which is the standard deviation of the residuals of the regression model, can be used to draw statistical inferences about the model performance.

Regression techniques were applied to correlate the IEU and IPEU with the eight input design variables. Tables 4.8 and 4.9 give a summary of the relationships obtained for the EnergyPlus simulations and the subsequent regression analysis. To correlate with IEU and IPEU, good fit linear regression models were formed for OV, SF, R_c, R_w and R_f, while WWR, LT and H/L were fit by cubic equations. With such correlations, all R^2 values were more than 0.9 and the strength of each mathematical expression was considered strong. By using these equations, the energy implications due to individual design parameters of daylighting can be reasonably predicted. The regression analyses demonstrate the energy performance of daylighting schemes in terms of each design variable which will be considered critical at the early design stage.

TABLE 4.8 Summary of regression relationships for the incremental annual electricity

Abb.	Input parameter	Linear regression $y = c + mx$			3rd order polynomial regression $y = A + Bx + Cx^2 + Dx^3$				
		c	m	R^2	A	B	C	D	R^2
WWR	Window to wall ratio				0	-6533.5	12490	-7077.5	0.993
LT	Light transmittance of windows				0	-6176.8	10821	-6020.7	0.987
OV	Projection ratio of overhang	-1021.1	236.5	0.982					
SF	Projection ratio of side-fins	-1027	103	0.968					
R_c	Reflectance of ceiling	-1019.5	-42.4	0.985					
R_f	Reflectance of floor	-1016.4	-67.3	0.982					
R_w	Reflectance of wall (internal surface)	-1011.4	-71.6	0.947					
H/L	Ratio of height of external obstruction to the separation (facing N,E,S,W)				-1034.5	75.4	5.41	-0.68	0.999

TABLE 4.9 Summary of regression relationships for the incremental peak electricity

Abb.	Input parameter	Linear regression $y = c + mx$			3rd order polynomial regression $y = A + Bx + Cx^2 + Dx^3$				
		c	m	R^2	A	B	C	D	R^2
WWR	Window to wall ratio				0	-3193.2	6113.9	-3041.1	0.974
LT	Light transmittance of windows				0	-3189.3	5814.1	-3359.2	0.970
OV	Projection ratio of overhang	-507.2	230.8	0.991					
SF	Projection ratio of side-fins	-500.6	53.5	0.979					
R_c	Reflectance of ceiling	-479.8	-81.2	0.975					
R_f	Reflectance of floor	-482.6	-71.2	0.985					
R_w	Reflectance of wall (internal surface)	-482.5	-69.5	0.982					
H/L	Ratio of height of external obstruction to the separation (facing N,E,S,W)				-501.6	3.39	6.36	-0.429	0.999

4.4 Summary of Key Findings

Field measurements of a high frequency dimming control in an open plan office were undertaken. Parameters considered important in the evaluation of daylighting performance, including daylight availability and indoor illuminance, electric lighting energy consumption and cooling requirement, were systemically measured and analysed. It was found that the peak transmitted daylight illuminance was recorded to be 43,000 lux and the major transmitted daylight illuminances were over 5,500 lux. A significant energy saving was investigated for electric lighting under the dimming control in the office in the measuring period. The measured lighting and cooling energy expenditures were also compared with the simulated results. It was found that the simulated results showed reasonably good agreement with the measured data. The MBE was found to range between -5.3 and 3.5% and the peak RMSE was 6.7% of the measured mean value. Using weather data of the year 2004, the annual lighting and cooling energy expenditures were simulated. With daylighting controls, the lighting and cooling energy expenditures can be reduced by 30 and 4%, respectively. It represents an annual energy reduction of 9% for the office. It is envisaged that more energy savings can be achieved in the reduction of heat dissipation from artificial lighting and, hence a lower cooling energy.

A sensitivity analysis was performed to test how the sensitivity and the output results would be affected by changes of the input parameters. In total, eight input parameters namely, WWR, LT, OV, SF, H/L, R_c, R_f and R_w affecting daylighting designs for an office building were selected. It was found that the IEU and IPEU were sensitive to envelope design parameters and external shadings, such as WWR, LT and H/L when daylighting was considered. Sensitivity of both IEU and IPEU showed similar patterns and the sensitivity coefficients were determined. The simple energy equations were also formed for the eight input parameters by using regression analysis. It is expected that the modelled regression equations will be particularly useful to the architects and building engineers during the initial design stage when different single design parameters are considered and assessed. The analyses in this study illustrate the potentials of a daylighting scheme that expresses the building energy consumption savings and peak electricity demand reductions in terms of a number of building envelope design variables. In Chapter 5, the energy performance of the generic office building due to various building envelope designs and daylighting schemes will be illustrated. Important features for daylighting schemes will be highlighted and implications for OTTV designs will also be discussed.

Chapter 5 Building Envelope Designs

5.1 General

The energy performance of a building is subject to building envelope design which determines its thermal response to the external weather conditions (Bouchlaghem, 2000). Optimising the design of building envelopes also depends on the appropriate solutions for various parameters of the visual, thermal and acoustical comfort of the occupants. To encourage energy-efficient building envelope designs, the Hong Kong Government issued the OTTV standard in 1995. Under this mandatory requirement, the impact of envelope options on thermal performance of an air-conditioned commercial building can be evaluated at the early design stage. By far, solar heat gain through fenestration is considered the largest contributor to building envelope cooling load (Yu and Chow, 2007) and the most important parameter for OTTV determinations (Lam et al., 1994). In Hong Kong, the high-rise and curtain walling office complexes with reflective glass and metal/stone cladding were popular in the 90s. A survey and field study of 41 government office buildings revealed that the average OTTVs increased from 21.6W/m^2 in the 1950s to 34.2W/m^2 in the 1990s (Lam et al., 2000). Such rising trend would impose too many constraints on architectural design and construction practice to meet the current Hong Kong OTTV standard of 30W/m^2.

The amount of daylight entering a building is mainly through window openings that provide the dual function of admitting light into the indoor spaces and connecting the outside world to the inside of a building. People expect good natural light in their working environment. On the other hand, natural light accompanies solar heat gain to a building. Therefore, in recent years, there has been an increasing interest in determining daylight and energy performances for buildings with different architectural and building envelope designs (Unver et al., 2004; Tzempelikos et al., 2007). The enlarged fenestration areas often result in larger OTTV. However, cooling requirement due to bigger glazing area could also be compensated from daylight-induced energy savings. It means that less building energy consumption may result with a larger OTTV if a proper daylighting control is employed. Therefore, selection of building envelopes should be determined to provide the lighting comfort requirement as well as energy conservation in the design process.

Nevertheless, the relationships between lighting, heating and in particular, cooling, and their implications for energy consumption in buildings are rather complex. Integrated lighting and thermal simulation tools are considered valuable design and analysis tools in analyzing the dynamic hourly interactions between the benefits of daylighting and extra cooling requirements due to larger OTTV. This chapter focuses on daylighting designs and OTTV implications through computer simulation analysis. Correlation models to determine annual electricity and peak loads (electricity demand and air-conditioning plant capacity) reductions with different envelope designs and daylighting schemes are established. Through graphical analysis, the fenestration effects were examined, and the energy expenditure and building energy performance are presented and discussed.

5.2 Envelope Design Elements

Several design considerations impacting transmitted heat gain and natural light affect a building in terms of form and shape. The most significant design determinant on daylighting and energy analysis is the geometry of a building's external walls and windows, and how each relates to each other. Building envelope plays the most important role to accomplish the required comfort conditions (i.e. visual, thermal and acoustical) of the occupants in a space. An understanding of the characteristics of the building envelope elements will provide the basis for optimising building form to achieve low energy design.

5.2.1 Overall Transfer Thermal Value (OTTV)

In Hong Kong, the OTTV is used as a regulatory control for building-envelope designs in commercial building development. The OTTV concept was initially introduced in the ASHRAE Standard 90A-1980 (ASHRAE, 1980). Strictly speaking, OTTV is an indication of the average heat gain through the building envelope. Three components of the heat gain are considered, namely conduction through an opaque surface, conduction through glass windows and solar radiation through glass windows. The general OTTV equation can be expressed as (ASHRAE, 1980):

$$\begin{aligned} \text{OTTV} &= (Q_{wc} + Q_{gc} + Q_{sol})/A_{tw} \\ &= [(A_w \, x \, U_w \, x \, TD_{eq}) + (A_g \, x \, U_g \, x \, DT) + (A_g \, x \, SC \, x \, SF)]/A_{tw} \end{aligned} \tag{5.1}$$

where Q_{wc} = heat conduction through opaque walls (W)

Q_{gc} = heat conduction through glass windows (W)

Q_{sol} = solar radiation through glass windows (W)

A_w = area of opaque wall (m²)

U_w = U-value of opaque wall (W/m²°C)

TD_{eq} = equivalent temperature difference (°C)

U_g = U-value of glazing (W/m²°C)

DT = temperature difference between exterior and interior design conditions (°C)

SF = solar factor (W/m²)

A_g = area of glazing (m²)

A_{tw} = total gross exterior wall area (m²) = $A_g + A_w$

The approach and equations for calculating the roof OTTV are similar to those for the walls. Calculations for the roof are often simpler because the roof usually does not contain a large amount of glazing, except for skylights over the atrium. The heat gain through the roof is generally small (i.e. small area and low thermal conductance) compared with that through external walls (Lam, 1995). In Hong Kong, it has been shown that among the three components of heat gain in the OTTV equation, solar radiation through fenestration is by far the most significant (Huang et al., 1989) and Q_{gc} is ignored in OTTV calculation (BD, 1995). The building variables controlling solar heat gain are shading coefficient (SC) and WWR, which are two parameters in the OTTV calculation. More solar heat gain contributes to more cooling requirements and hence larger air-conditioning plants (Lam and Hui, 1996b). Higher solar heat gain, however, could also mean more daylight available for a daylighting scheme. There is scope for integrating daylight with electric light to save building energy use. It is argued that the increased cooling load and electricity expenditure caused by larger window areas could be offset by daylight-induced savings. This would allow local architectural designs and construction practices to have a more flexible design strategy as modern architecture has been characterized by the use of curtain walls in buildings. This leads to architects and building engineers expressing a common desire for more information on the energy performance of buildings when such a design scheme is adopted despite the fact that daylighting credits are not included in the current OTTV calculation.

5.2.2 Daylighting Aperture (DA)

From the comparisons of cooling and energy performance between designs with and without daylighting schemes, it has been shown that daylight admitted through the building envelope offers an opportunity to significantly reduce lighting requirements and cooling loads. The building envelope, primarily the glazing, is a major variable in determining the peak demands and energy consumption. Generally speaking, as the area of fenestration systems increases, the amount of daylight received in a space also increases. However, the light transmittance (LT) of the glazing material can also effectively control the amount of visible light that is allowed to enter. To better understand these interactions, daylighting aperture (DA) of a glazing system, which is determined by multiplying the LT by the WWR was used for the analysis of daylighting and energy performance (Lam and Li, 1999).

$$\mathrm{D}A = \mathrm{LT} \times \mathrm{WWR} \tag{5.2}$$

Daylighting aperture determines the amount of daylight entering a building and it can also be useful in evaluating the daylighting potential of a schematic building configuration.

5.3 Daylighting Performance and Energy Implications

For commercial buildings with central air-conditioning plants and fixed operating hours, the original OTTV concept can be extended to deal with cooling energy due to heat gains through building envelopes. Lam (1995) has correlated OTTVs with annual chiller loads (i.e. total cooling loads imposed on the chillers) using computer simulation techniques for a generic office building. Analysis of the simulation results of the base-case model is important to understand the components and building parameters of the model. A similar approach is adopted for this study. The reference office building in Chapter 3 was employed to analyze the energy implications on different envelope designs. The IWEC weather database was used to perform hour-by-hour calculations of energy performance for the reference building in EnergyPlus. Based on a series of systematic computer simulation studies, regression models and simple design tools can be developed to correlate thermal and energy performance indicators (e.g. building energy consumption and peak cooling load) with key design variables such as window area and glass types. It is envisaged that such correlation relationships and simple design tools can give designers certain basic and concise insights into the interdependency between building energy use and these design parameters. Key fenestration parameters concerning OTTV determinations and a daylighting scheme were also identified and used to perform a series of computer simulations.

5.3.1 Envelope Heat Gains

Based on the proposed generic building envelope, the OTTV equation and parameters from the OTTV code, Q_{wc}/A_{tw}, Q_{sol}/A_{tw}, and OTTV in the four principal orientations (i.e. North, East, South and West) and the whole building were computed and a summary is given in Table 5.1. In subtropical Hong Kong, there are still significant cooling requirements during intermediate season and early winter due mainly to substantial amounts of internal load – people, electric lighting and office equipment. As such, beneficial conduction heat loss through the glass windows tends to cancel out the unwanted heat gain during the main cooling season. On an annual basis, the net conduction heat through glass windows, Q_{gc}, (Eq.(5.1)), tends to be small, and was therefore, not included in the 1995 OTTV regulation and no *DT* data are provided in the local OTTV code. It can be seen from Table 5.1 that the solar radiation component dominates the OTTV determinations, accounting for over 85% in all cases. The north orientation has the lowest OTTV of 20.6W/m², while the OTTVs for other vertical surfaces are between 34 and 37W/m². This is because the solar radiation received by north-facing surfaces is mainly diffuse and the TD_{eq} and *SF* provided by the Code of Practice are the smallest among all vertical surfaces. The OTTVs for the east and the west facades are not the same because the TD_{eq} and SF given are different for these two orientations.

TABLE 5.1 The OTTV for a base-case generic building

OTTV (W/m^2)	North	East	South	West	Whole Building
Q_w/A_i	2.8	5.5	4.1	4.7	4.3
Q_s/A_i	17.8	28.8	32.7	30.0	27.3
Total	20.6	34.3	36.8	34.7	30

To get some idea of the amount of conduction heat gain through the windows, Q_{gc}, temperature difference between the exterior and interior design conditions, *DT*, was determined for two different periods – six-month cooling season (May – October) and nine-month cooling season (mid-March – mid-November). A 10-year (1980 – 1989) long-term hourly ambient temperature database was used. The temperature difference is 1.8 and 0.3ºC for the six and eight-month cooling seasons respectively, and the corresponding Q_{gc}/A_i are 4.4 and 0.7 W/m^2. In subtropical Hong Kong, the cooling season for domestic buildings is from May to October. For non-domestic buildings (e.g. offices) the cooling season is longer, from mid-March to mid-November, due mainly to the comparatively higher internal heat gains from electric lighting, office equipment and occupants (Lam et al., 1994). Therefore, for non-domestic buildings with high internal loads, conduction heat gain during the cooling season is small, about 2% of the 30W/m^2 OTTV shown in Table 5.1. The current OTTV regulation only applies to commercial buildings and the aim of the study is to demonstrate the significance of including daylighting credits in the current Hong Kong OTTV standard. The OTTV determinations, therefore, are based on the OTTV equations and parameters provided in the Code of Practice for Hong Kong. Nonetheless, it is believed that the current OTTV formulation should be re-examined with a view to identifying special cases (e.g. full glazing with small internal heat gain), in which the exclusion of Q_{gc} might lead to a significant underestimation of conduction heat gain through the building envelope.

5.3.2 Effect on Building Energy Consumption

From the comparison of cooling load and energy performance between the two schemes (i.e. design with and without daylighting), it has been shown that daylight admitted through the building envelope offers an opportunity to significantly reduce lighting requirements and, to a lesser extent, cooling loads. The building envelope, primary the glazing, is a major variable in determining the peak demands and energy consumption. The SC dominates solar gains and OTTV calculations, and thus affects the peak cooling demand and energy consumption of a building. The LT of the glass offsets the electric lighting energy use and the cooling requirements due to heat dissipation from the artificial lighting system. Therefore, a detailed analysis of the benefits of lighting energy savings against the detrimental effects from solar heat gain is essential for the development of adding daylighting credits in OTTV code as well as encouraging energy-efficient building envelope designs. To facilitate an understanding of the factors affecting fenestration system performance, key window variables are often changed parametrically in computer simulations. Regression techniques are then used to study the effect of various parameters on building energy performance. In this study, annual building energy consumption was correlated with the glazing variables through regression analysis.

For a given glazing type, the critical variable determining solar heat gains and the amount of daylight entering a building is the glazing area which is often expressed in the form of WWR. A large window area will, on one hand, result in more cooling requirements due to an increase in solar radiation. It, however, will also admit more natural daylight and may reduce electric lighting consumption. To better understand these interactions, two parameters: OTTV and DA were used in the analysis. Lam and Li (1999) assessed the performance of general daylighting schemes and used solar aperture (SA), which is WWR times SC to correlate with DA. This study focuses on more specific cases and the analyses are according to the OTTV equations and parameters provided by the OTTV code.

Without Daylighting

The base-case generic office building was used to carry out a series of simulations with the fenestration design being changed systematically. Three single glazing types, namely clear glass (SC = 0.9, LT = 0.85, U-value = 6W/m^2°C), tinted glass (SC = 0.7, LT = 0.5, U-value = 6.2W/m^2°C) and reflective glass (SC = 0.4, LT = 0.3, U-value = 5.6W/m^2°C), which are commonly found in Hong Kong (Li and Tsang, 2008), were simulated. In addition to the base-case (i.e. 43% WWR using reflective glass), glazing area was varied using 14 WWRs ranging from 5 to 70% at 5% intervals. In total, 43 simulation runs for the non-daylighting scheme (i.e. three simulation runs for every WWR plus the base-case) were performed. These 43 sets of simulation results were used for the subsequent regression analysis. To better understand the electricity consumption due to solar heat gain, incremental electricity use for non-daylighting scheme (IEU_O) was correlated with OTTV. The differences between the total building energy consumption of the 43 simulation cases and that of the base-case ($IEU_{O,B}$) (i.e. the building complies with the local OTTV limit of 30W/m² without daylighting controls) were correlated with their corresponding OTTVs and are shown in Figure 5.1. It can be seen that the $IEU_{O,B}$ correlates almost linearly with OTTV. The slight non-linearity may be due to the change of U-value for different glazing types. Through regression analysis, $IEU_{O,B}$ for the whole building (i.e. the sum of the four perimeter zones) can be expressed in terms of OTTV as follows:

$$IEU_{O,B} \text{ (in MWh)} = 32.5 \text{ (OTTV} - 30) \tag{5.3}$$

The R^2 is 0.97, indicating that 97% of the changes in $IEU_{O,B}$ can be explained by the variations in OTTV. Without daylighting controls, only 16 out of 43 simulation runs show less OTTV and electricity use than the base-case and all the 16 cases have WWR less than 0.43. This indicates that the OTTV standard imposes heavy constraints on building envelope designs and contradicts modern architecture. The electricity consumption for each perimeter zone was also determined separately. Similar linear correlations were found for the four perimeters zones, but the magnitude of electric energy use and the rate of increase vary and the effects of orientation can be noted. The base-case OTTV for the four individual perimeter zones presented in Table 5.1 were used for the regression analysis. The regression results for individual perimeter zones are expressed as:

$$IEU_{O,N} \text{ (in MWh)} = 6.47 \text{ (OTTV} - 21) \text{ (for north perimeter zone } R^2\text{=0.99)} \tag{5.4}$$

$$IEU_{O,E} \text{ (in MWh)} = 7.18 \text{ (OTTV} - 34.8) \text{ (for east perimeter zone } R^2\text{=0.98)} \tag{5.5}$$

$$IEU_{O,S} \text{ (in MWh)} = 6.58 \text{ (OTTV} - 37.5)\text{(for south perimeter zone } R^2\text{=0.97)} \tag{5.6}$$

$$IEU_{O,W} \text{ (in MWh)} = 7.33 \text{ (OTTV} - 35.4) \text{ (for west perimeter zone } R^2\text{=0.99)} \tag{5.7}$$

The north perimeter zone basically only receives diffuse radiation, therefore the OTTV and $IEU_{O,N}$ determined from Eq.5.4 should be relatively small. East, south and west perimeter zones admit direct sunlight and thus have similar coefficients of higher values. With all of the R^2 values being greater than 0.96, the correlations between the IEU_O and OTTV are considered strong.

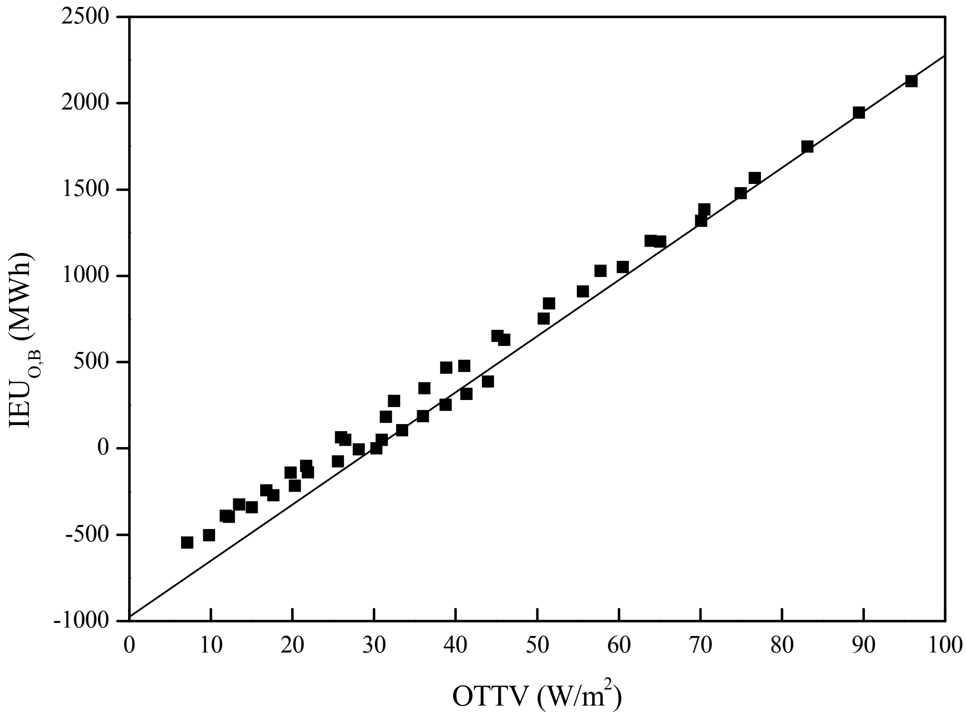


Figure 5.1 Correlations between incremental electricity use and OTTV

With Daylighting

Similarly, a total of 43 computer simulation runs with daylighting schemes were conducted, and the simulated results were used for the regression analysis. To study the electricity savings, the incremental electricity use due to daylighting (i.e. difference in the electricity expenditure between buildings with and without daylighting controls for the same fenestration designs), IEU_D, were computed and correlated with the DA, and are shown in Figure 5.2. As the DA increases initially from 0, there is a large reduction in lighting energy, indicating that the capacity of daylight to replace artificial lighting is high. However, as DA continues to increase, daylighting does not significantly contribute to additional lighting energy savings but degrades progressively. It can be seen that there are very small additional energy savings beyond 0.4 DA. The findings are similar to the work reported by Sullivan et al. (1992b) in California and Huang et al. (1989) in Singapore. Detailed comparison of results with similar research work (i.e. office buildings with daylighting schemes) conducted in various areas is not possible because the weather database, material used, and lighting, occupancy and equipment schedules are not the same. Through regression analysis, it has been found that the incremental electricity use due to daylighting for the whole building ($IEU_{D,B}$) can be correlated with the daylighting aperture as follows:

$$IEU_{D,B} \text{ (in MWh)} = 1610\,(e^{-6DA} - 1) \qquad (5.8)$$

The R^2 value is 0.98, indicating that 98% of the variations in IEU can be accounted for by the variations in DA. This regression result is not the same as the findings of Lam and Li (1999) and the reasons are the different diffuse and direct solar radiation databases used and greater number of simulation runs conducted in this thesis. Again, the electricity savings for the four perimeter zones were also determined. Similar correlation relationships between the incremental energy use and DA were found and are expressed as:

$$IEU_{D,N} \text{ (in MWh)} = 360\,(e^{-7DA} - 1) \text{ (for north perimeter zone } R^2\text{=0.98)} \qquad (5.9)$$

$$IEU_{D,E} \text{ (in MWh)} = 371\,(e^{-5DA} - 1) \text{ (for east perimeter zone } R^2\text{=0.97)} \qquad (5.10)$$

$$IEU_{D,S} \text{ (in MWh)} = 387\,(e^{-8.9DA} - 1) \text{ (for south perimeter zone } R^2\text{=0.96)} \qquad (5.11)$$

$$IEU_{D,W} \text{ (in MWh)} = 409\,(e^{-7.7DA} - 1) \text{ (for west perimeter zone } R^2\text{=0.97)} \qquad (5.12)$$

The magnitude of the energy reduction is smaller compared with the whole building. All of the R^2 values for the four perimeter zones exceed 0.95 indicating a strong correlation between the IEU_D and DA.

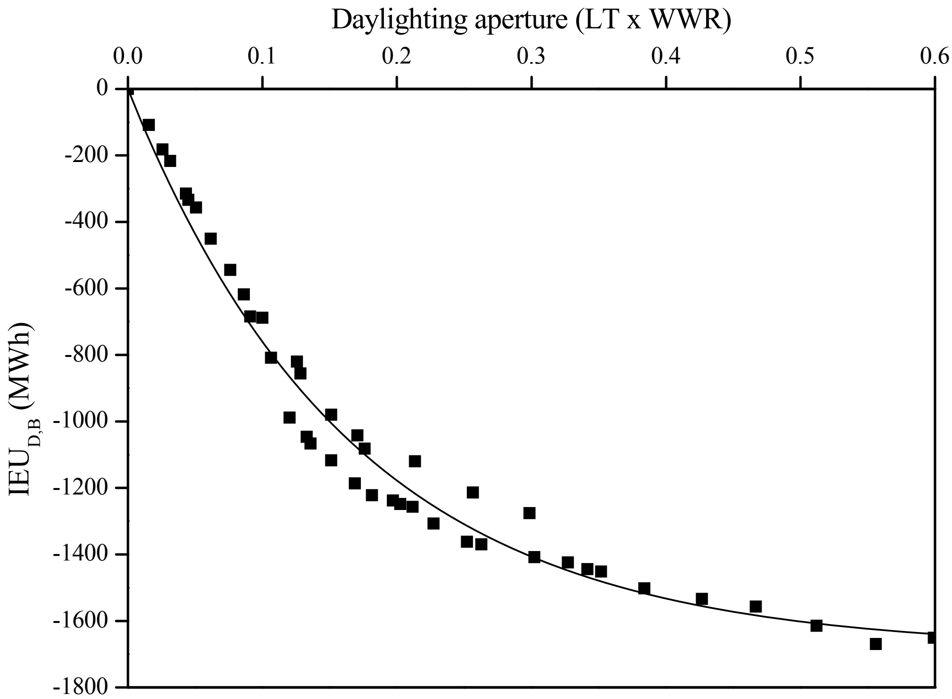


Figure 5.2 Correlation between incremental electricity use and DA

5.3.3 Simple Design Graphs

The overall energy performance of the fenestration system can be determined by using the OTTV (i.e. thermal heat gain) and daylighting increments. The correlation relationships between IEU_O and OTTV, and IEU_D and DA shown in Figures 5.1 and 5.2 were combined to form a composite set of data indicating energy use as a function of these two variables. Figure 5.3 shows the contours of expected incremental electricity use as a function of OTTV and DA for all the four perimeter zones together (i.e. the whole building). These contours reflect the overall energy performance of different building envelope designs in terms of different combinations of opaque wall areas and window types and areas. The zero overall IEU_A (the difference between IEU_O and IEU_D per building gross floor area) line ($0kWh/m^2$), refers to the same energy expenditure as the base-case building with an OTTV of $30W/m^2$ (i.e. the OTTV limit for Hong Kong) and no daylighting control. Figure 5.3 shows that for a particular building envelope design, as the WWR increases, various combinations of OTTV and DA will result in different electricity consumption with top-up lighting controls. Positive values in the IEU_A mean that more energy is consumed compared with the base-case building envelope design and these occur when OTTVs are greater than $30W/m^2$ and in general without daylighting controls (i.e. do not comply with the local regulation). Negative values, however, indicate the amount of energy savings. The combinations of OTTV and DA along the zero value line denote the same electricity consumption as the base-case generic building with an OTTV of $30W/m^2$. This indicates that a higher OTTV and DA can result in the same or even less electricity consumption as the base-case building envelope design if a proper daylighting control is adopted. A high OTTV means more heat gain (especially solar heat) and hence requires more cooling energy. For OTTV $\geq 80W/m^2$, no energy savings can be obtained for all DA values with daylighting controls. This means that with daylighting controls the generic building with OTTV up to $80W/m^2$ may consume the same amount of energy as the base-case generic building without daylighting controls. This finding supports the argument that adding daylighting credits to current OTTV standard can allow more flexibility in building envelope designs and encourage building energy conservation. Obviously, architects and building designers should avoid the likely problems of glare, excessive brightness ratios, and the thermal discomfort when such high OTTV building envelope designs are adopted.

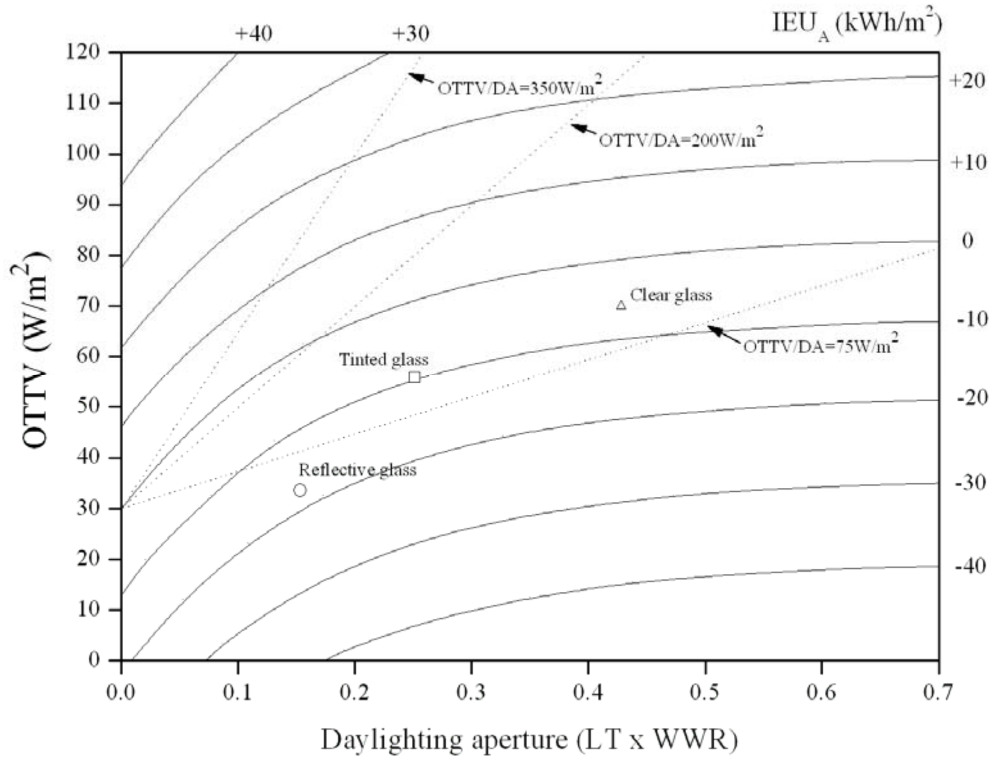


Figure 5.3 Contour of equal incremental electricity use for the whole building (○, reflective glass; □, tinted glass; Δ, clear glass)

The ratio of OTTV to DA (OTTV/DA), which modifies the ratio of LT to SC (Arasteh et al., 1985), can be used to measure the energy efficiency of a particular building envelope design in terms of daylighting potential and the likely impact on cooling energy. The same OTTV/DA can be obtained with different combinations of DA and OTTV. For a fixed OTTV/DA value, the energy performance can vary a great deal. For OTTV/DA = 200W/m^2 from the reference point (30W/m^2 OTTV and 0 DA), IEU$_A$ varies from about –2.5kWh/m^2 (energy savings) to over +23kWh/m^2 (more energy consumed), depending on the different combinations of OTTV and DA values (i.e. different building envelope designs). This indicates that OTTV/DA in itself is not a sufficient parameter to determine energy performance. Nevertheless, OTTV/DA can provide an indication of the likely energy efficiency and the optimum OTTV and DA. For instance, with OTTV/DA = 200W/m², the optimum values can be determined by moving away from the reference point along the 'OTTV/DA = 200W/m² line'. Initially, the reduction in lighting energy outweighs the increase in cooling requirement up to OTTV = 49/m² and DA= 0.1. Beyond this optimum point, a reduction in electric lighting becomes progressively smaller and the cooling energy penalty begins to outweigh the natural daylight benefit. It can also be seen that for OTTV/DA ≥ 350W/m², more energy is always required regardless of the daylighting aperture in its building envelope design, indicating that cooling penalty due to solar heat always exceeds natural daylight benefits even though daylighting design is used. The smaller the OTTV, the lower the energy penalty will be. For OTTV/DA ≤75, there will always be energy savings. A comparative energy performance study can also be conducted for different glass types. To illustrate this, the three types of glass commonly used in Hong Kong buildings are also shown in Figure 5.3, based on which the relative energy performance of different fenestration design schemes can be assessed. With a WWR of 0.5, reflective glass admits small amounts of solar heat and natural light. The DA is only 0.15 and the OTTV is just over 30W/m^2, and these give an IEU_A of 17.5kWh/m^2. The DAs for clear glass and tinted glass are 0.25 and 0.43, respectively. A higher LT allows more daylight and hence less electricity consumption for artificial lighting and bigger reductions in sensible heat gain from electric lights compared with reflective glass. However, tinted glass and clear glass contribute to higher OTTV values (55W/m^2 for tinted glass and 70W/m^2 for clear glass), which indicate more solar heat entering the interior spaces. The overall effects are that clear glass consumes about 4kWh/m^2 more than tinted glass, which, in turn, is about 12kWh/m^2 more in energy expenditure than reflective glass.

Similarly, the same approach can be extended to develop contours of incremental electricity use as a function of the OTTV and DA for each of the four perimeter zones. Figures 5.4 and 5.5 show the contours for the north and south perimeter zones, respectively. It appears that for a given OTTV and DA, the north zone consumes more energy than the south perimeter zone. For example, at OTTV = 90W/m^2 and DA = 0.4, IEU$_A$ is +24kWh/m^2 for the north perimeter zone and +0kWh/m^2 for the south perimeter zone. However, a detailed analysis of the energy performance due to building envelope design should include the WWR and the orientation effect on solar heat. Again, the three types of glass (i.e. clear, tinted and reflective) with the maximum WWR of 0.7 are also plotted in the two figures. It can be seen that although the three types of glass have the same DA values for the two perimeter zones, the OTTVs are quite different, resulting in substantial variations in electricity use. For a north-facing curtain walling office, a negative IEU$_A$ (i.e. overall daylighting energy savings per unit floor area) can be observed for each type of glass. This is because the north-facing windows receive relatively smaller amounts of solar heat as they mainly admit the diffuse solar component. The OTTVs are less than 70W/m^2 for all DA. However, it can be seen that for the south perimeter zone, the clear glass and tinted glass result in high OTTVs (i.e. 95W/m^2 for tinted glass and 120W/m^2 for clear glass) and positive IEU$_A$ values. With daylighting controls, only reflective glass with the OTTV = 55W/m^2 can give less energy consumption than the base-case building envelope design.

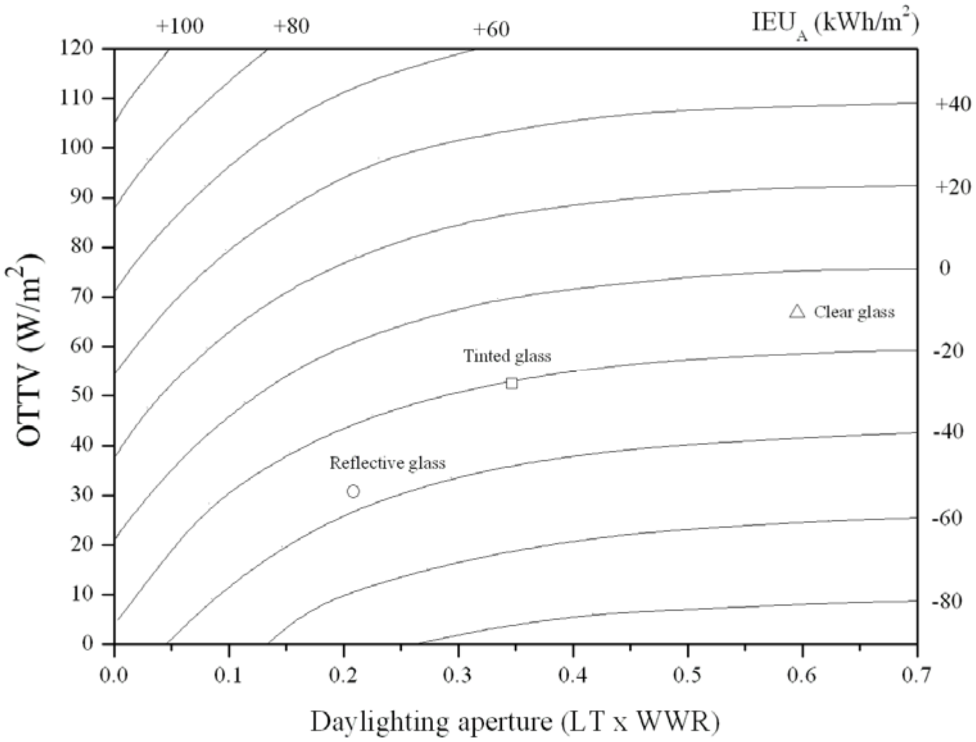


Figure 5.4 Contour of equal incremental electricity use for a north perimeter zone (○, reflective glass; □, tinted glass; Δ, clear glass)

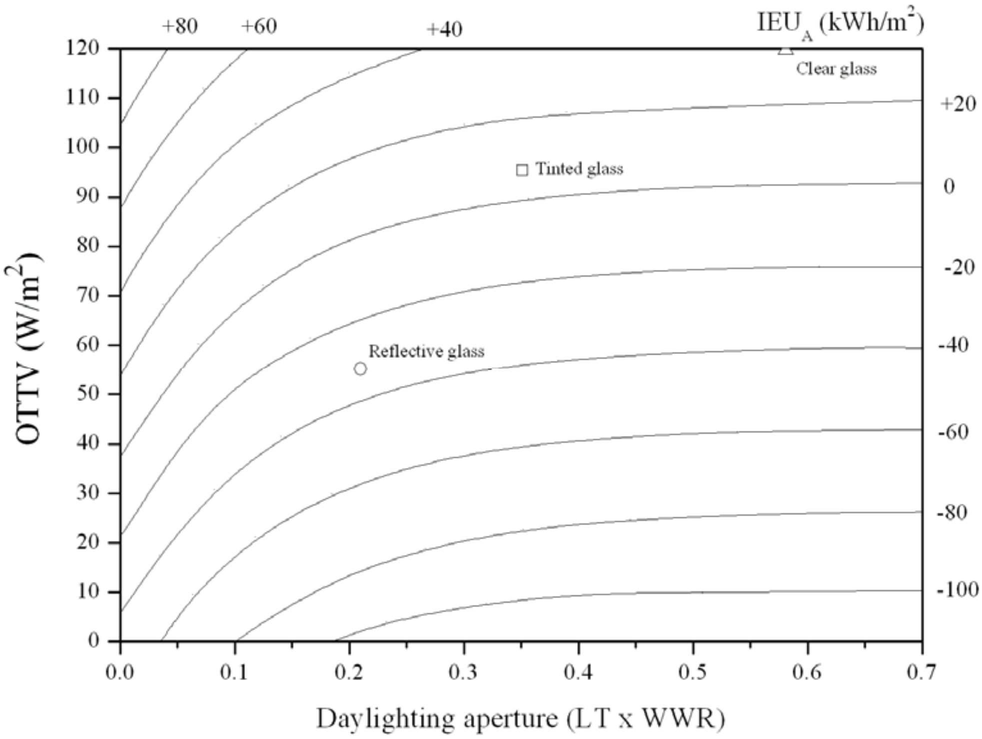


Figure 5.5 Contour of equal incremental electricity use for a south perimeter zone (○, reflective glass; □, tinted glass; Δ, clear glass)

Figures 5.6 and 5.7 show the simple design graph for the east and west perimeter zones, respectively. Similar patterns have been found for the east and west perimeter zones. The electricity use for east and west-facing offices is in between south and north-oriented. For example, at OTTV = 90W/m^2 and DA = 0.4, IEU_A is +16kWh/m^2 for the east perimeter zone and +5kWh/m^2 for the west perimeter zone. It is interesting that the energy consumption of north and east-facing offices are very close at the zero overall IEU_A line which is mainly because a high portion of solar heat gain is received in the afternoon (i.e. shorter business hours, 8am to 12pm, in the morning). Most of the solar heat obtained is diffuse-oriented for east-facing surfaces (Li, 1997). The findings show that solar heat affects the OTTV determination significantly and hence varies the trade-off between the beneficial natural daylight and unwanted solar heat gain. This suggests a possibility of using different building envelope designs for different orientations to achieve optimum energy performance as well as cost-effective designs. Overall, daylighting is proved to be a useful strategy in the design of energy-efficient buildings. It is beneficial and practical to incorporate daylighting credits into the OTTV concept.

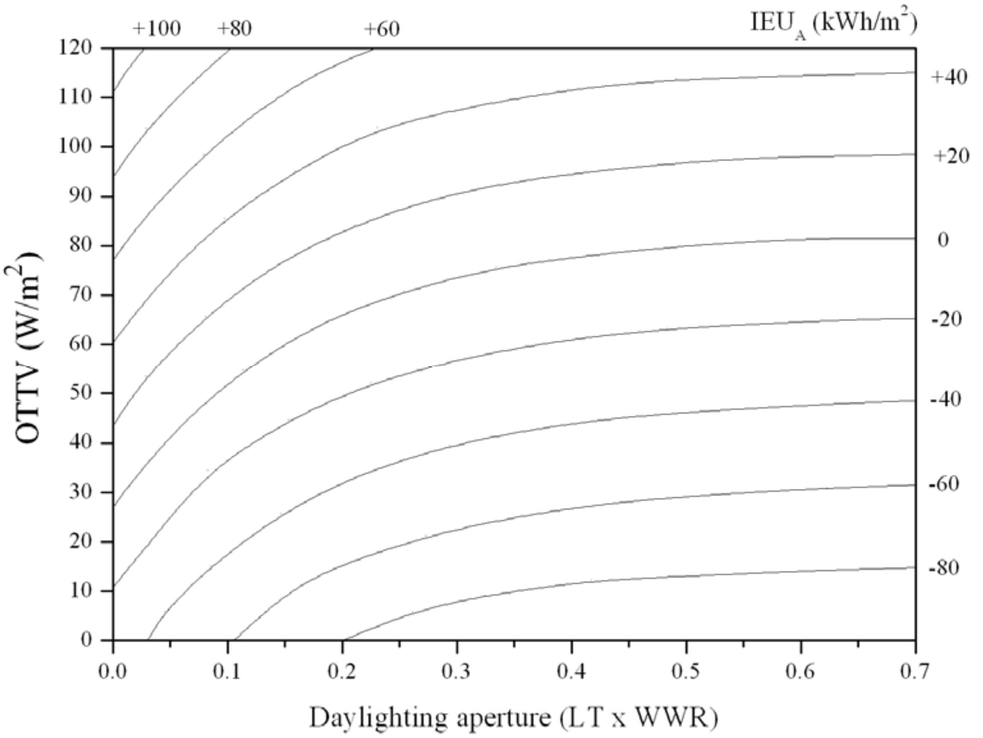


Figure 5.6 Contour of equal incremental electricity use for an east perimeter zone

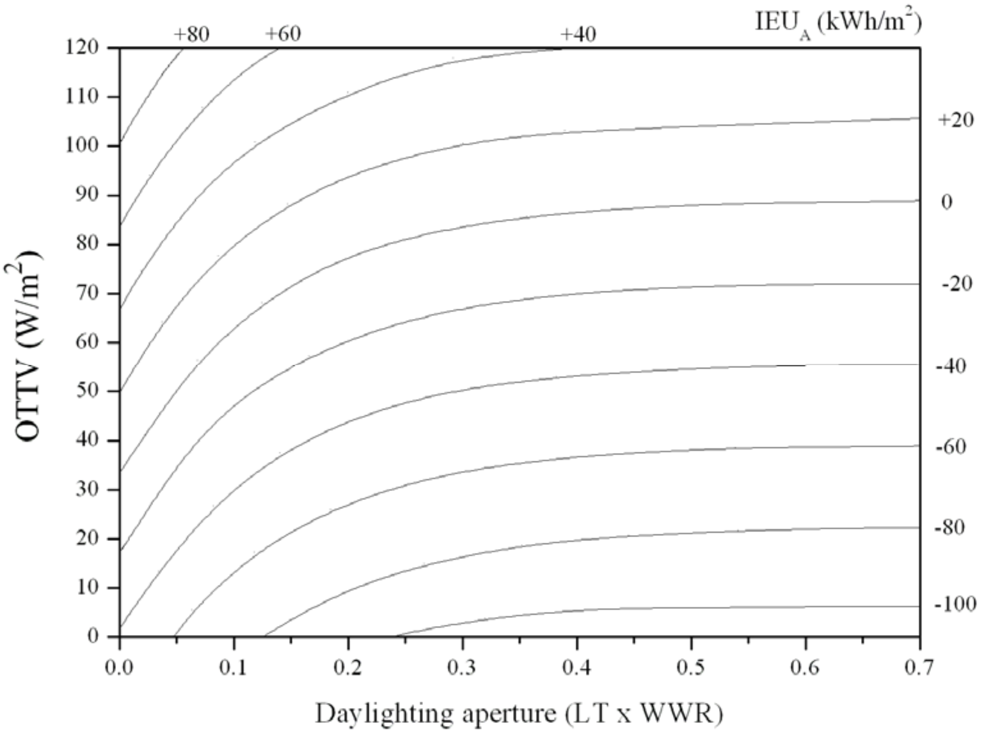


Figure 5.7 Contour of equal incremental electricity use for a west perimeter zone

5.4 Daylighting Performance and Peak Load Determination

Energy Savings resulting from daylighting mean not only reduced annual electricity use, but also lower peak electrical demands and cooling loads and the potential for selecting smaller HVAC plants (Lam and Li, 1999). It implies that the initial costs of HVAC systems and electrical installations can be lowered. Peak cooling plant demands and peak total electricity demands were also calculated from the above 43 simulations cases. Since selection of power supply system and central cooling plant are based on the building block loads, therefore, peak loads of the four perimeter zones have not be considered in this study. Correlation of the building peak loads and the building envelope elements was developed through regression analysis.

5.4.1 Effect on Peak Loads

Without Daylighting

The 43 sets of simulation results were used for the subsequent regression analysis. To better understand the peak electricity consumption variations due to solar heat gain, a term called incremental peak electricity use ($IPEU_o$) was correlated with the corresponding OTTV. The $IPEU_o$ is the difference between the peak electricity demand of the individual 43 simulation cases and that of the base-case building. Figure 5.8 presents such correlation. An almost linear correlation between the $IPEU_O$ and OTTV can be observed. It shows that peak electricity use is greatly dependent on building envelope design. The slight non-linearity may be due to the change of U-value for different glazing types. Through regression analysis, $IPEU_o$ can be expressed in terms of OTTV as follows:

$$IPEU_O \text{ (kW)} = 15.4 \text{ (OTTV} - 30) \quad (5.13)$$

The R^2 is 0.98, indicating that 98% of the changes in $IPEU_O$ can be explained by the variations in OTTV. Without daylighting controls, only 16 cases with WWR less than 0.43 show smaller OTTV and less peak electricity use than the base case. It indicates that the OTTV standard tends to impose constraints on building envelope designs and might not be conducive to innovative, energy-efficient modern architecture.

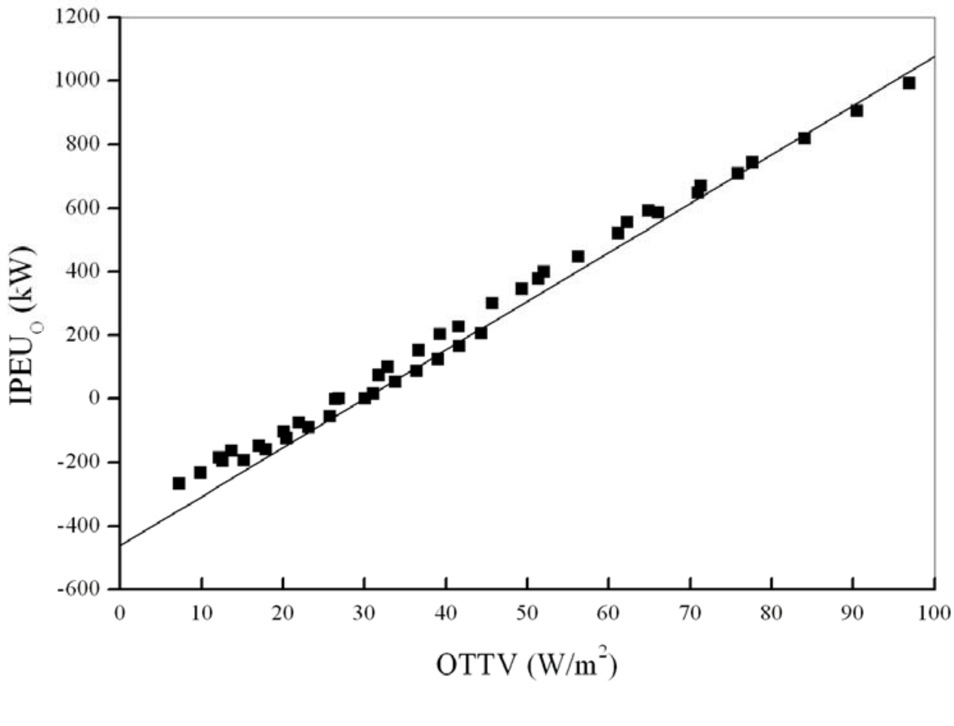


Figure 5.8 Correlation between incremental peak electricity use and OTTV

The method can also be used to correlate the incremental peak cooling plant demand ($IPCPD_O$) with the OTTV. The $IPCPD_O$ is the difference between the peak cooling plant demand of the individual 43 simulation cases and that of the base case. The results can give architects and engineers some idea of the likely variations of the cooling plant capacity due to changes in the OTTV. The peak cooling plant demands were obtained based on the same 43 simulation runs. Figure 5.9 shows the similar linear correlation of $IPCPD_O$ and OTTV. It can be seen that peak electricity use would be increased if higher cooling load is required. The regression results are expressed as:

$$IPCPD_O \text{ (kW)} = 30.5 \text{ (OTTV} - 30) \quad (5.14)$$

With the R^2 of 0.98, the correlation between $IPCPD_o$ and OTTV is considered very strong.

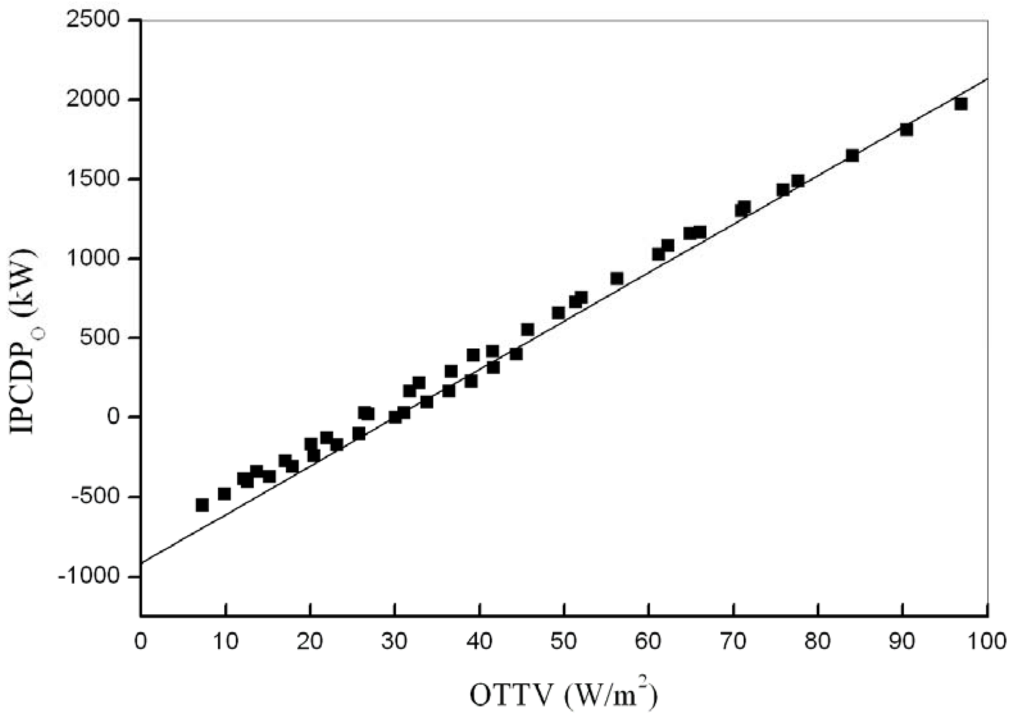


Figure 5.9 Correlation between incremental peak cooling plant demand and OTTV

With Daylighting

Similarly, the simulated peak loads of the 43 simulation runs with daylighting schemes were used for regression analysis. To study the incremental peak electricity use due to daylighting ($IPEU_D$), the differences in the peak electricity use between buildings with and without daylighting controls for the same building envelope designs were computed and correlated with the DA. Figure 5.10 presents the results. As the DA increases initially from 0, there is a large drop in peak electricity use, indicating that the capacity of daylight to replace artificial lighting and the reduction in heat dissipation from the electric lighting installation are high. However, as DA continues to increase, daylighting does not significantly contribute to additional peak energy reductions but degrades progressively. It can be seen that beyond 0.4 DA, there are almost no further energy reductions. Through regression analysis, it has been found that the incremental peak electricity use for the building can be correlated with the DA as follows:

$$IPEU_D \text{ (kW)} = 723 \left(e^{-7.3DA} - 1\right) \quad (5.15)$$

The R^2 value is 0.97, indicating that 97% of the variations in $IPEU_D$ can be accounted for by the variations in DA, and once again the correlation is considered strong.

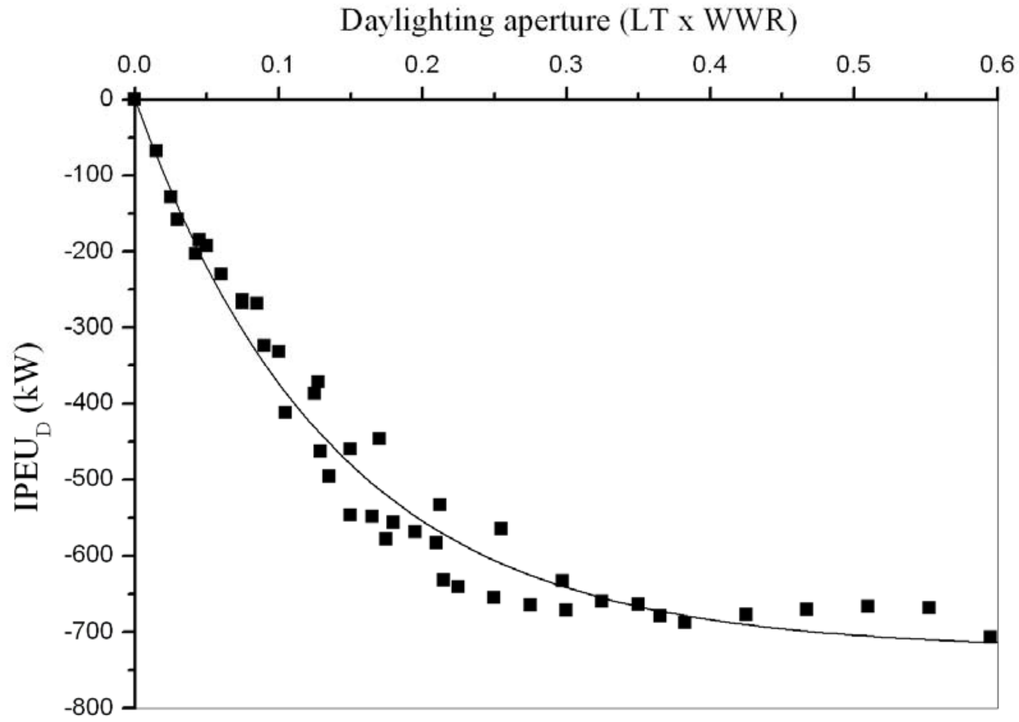


Figure 5.10 Correlation between incremental peak electricity use and DA

To study the air-conditioning load reduction, the difference in the incremental peak cooling plant demand between buildings with and without daylighting controls for the same building envelope designs ($IPCPD_D$) were also determined. Similar features are shown in Figure 5.11. Through regression techniques, R^2 value was computed as 0.94, representing a good correlation relationship. Again, the $IPCPD_D$ is expressed with an exponential function of DA as:

$$IPCPD_D \text{ (kW)} = 663\ (e^{-7DA} - 1) \tag{5.16}$$

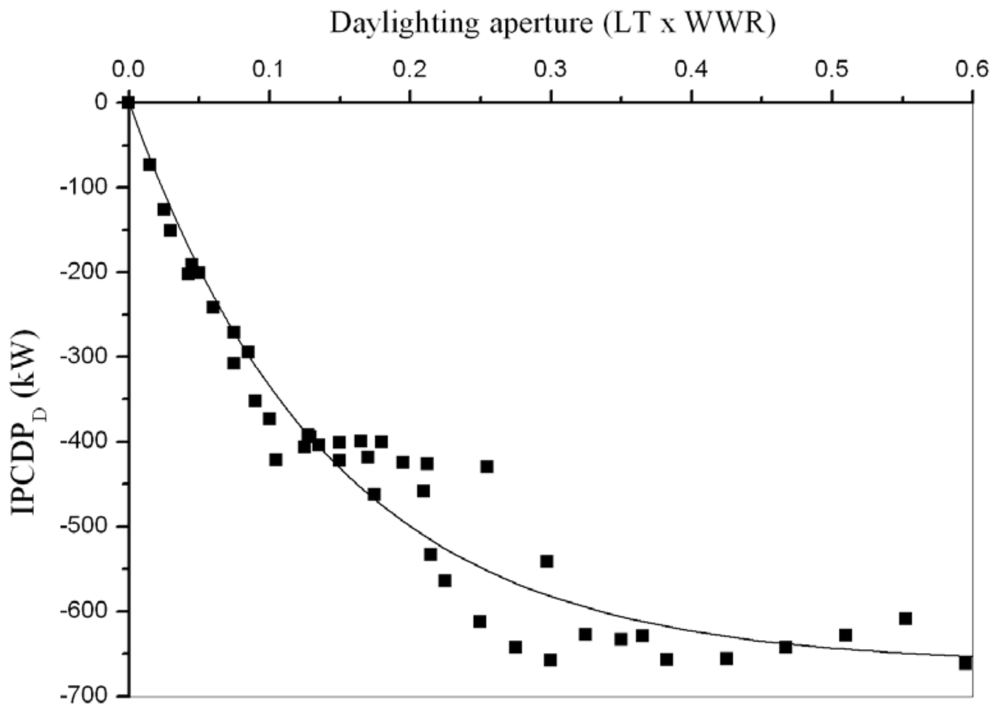


Figure 5.11 Correlation between incremental peak cooling plant demand and DA

5.4.2 Simple Design Graphs

The overall peak electricity demand variations can be computed by using the OTTV and daylighting increments. The correlation relationships between overall $IPEU_O$ (i.e. difference between the peak electricity use with various building envelope designs and the building which complies with the local OTTV limit of 30W/m² without daylighting controls) and OTTV, and $IPEU_D$ (difference in the peak electricity demand between buildings with and without daylighting controls for the same building envelope designs) and DA shown in Figures 5.8 and 5.10 were combined to form a composite set of data indicating peak electricity use as a function of these two variables. Figure 5.12 shows the contours of expected incremental peak electricity use as a function of OTTV and DA for the whole building. These contours reflect the overall peak electricity use variations of different building envelope designs in terms of different combinations of opaque wall areas and window types and areas. The zero $IPEU_A$ (i.e. the difference between $IPEU_O$ and $IPEU_D$ per building gross floor area) line ($0W/m^2$) refers to the same peak electricity use as the base-case building with an OTTV of $30W/m^2$ and no daylighting control. For a particular glazing building envelope design, as the WWR changes, various combinations of OTTV and DA will result in different peak electricity use with top-up lighting controls. Positive values in the $IPEU_A$ mean that there are higher peak electricity loads compared with the base-case building envelope design. These appear when OTTVs are more than $30W/m^2$ (i.e. do not comply with the local regulations) and in general without daylighting controls. Negative values, however, indicate peak electricity load reductions. The combinations of OTTV and DA along the zero value line denote the same peak electricity use as the base-case generic building with an OTTV of $30W/m^2$. This indicates that a higher OTTV and DA can give the same or even less peak electricity use as the base-case building envelope design if a proper daylighting control is employed. High DA admits more daylight. However, a diminishing return can be observed for DA > 0.4 and further reduction in peak electricity use can only be achieved by lowering the OTTV. For OTTV ≥ $70W/m^2$, no peak electricity use reductions can be obtained for all DA values with and without daylighting controls. It shows that with daylighting controls the generic building with OTTV up to $70W/m^2$ may consume the same peak electricity use as the base-case generic building without daylighting controls. This finding supports the argument that adding daylighting credits to the current OTTV standard can reduce the peak electricity demands and encourage building energy conservation. Obviously, architects and building designers should avoid the likely problems of glare, excessive brightness ratios, and thermal discomfort when such high OTTV building envelope designs are considered.

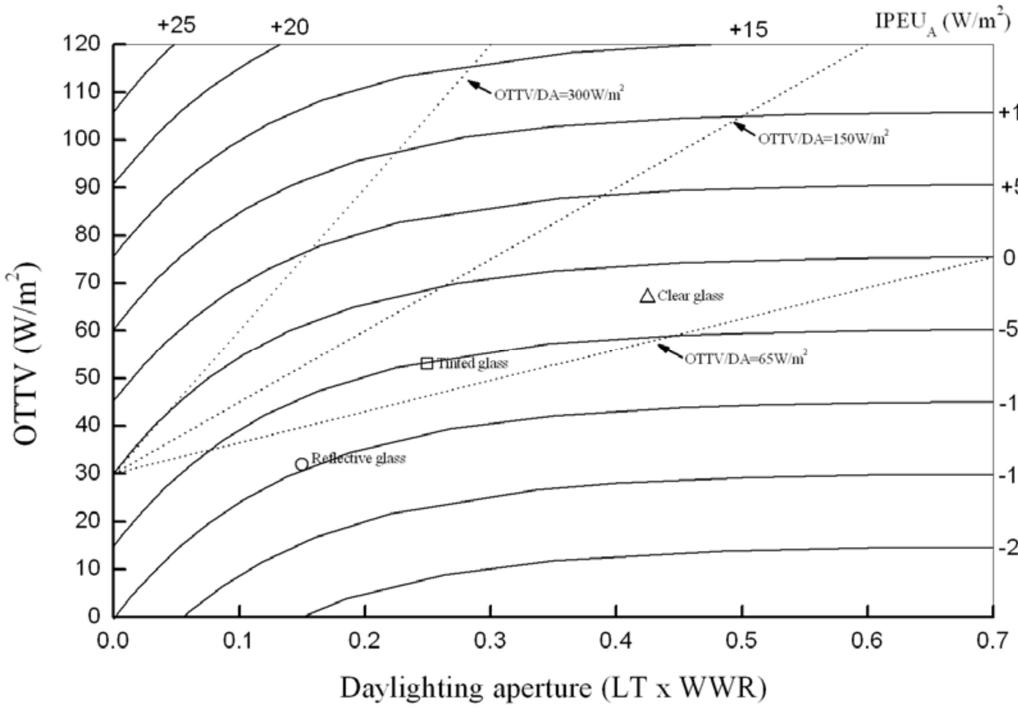


Figure 5.12 Contour of equal incremental peak electricity use (○, reflective glass; □, tinted glass; Δ, clear glass)

The ratio of OTTV to DA (OTTV/DA) can be used to measure the energy efficiency of a particular building envelope design in terms of daylighting potential and the likely impact on cooling energy requirements. For a building with large window areas such as high-rise commercial buildings with curtain walls, OTTV/DA can be considered as the thermal feature of a particular glazing type. The same OTTV/DA can be obtained with different combinations of DA and OTTV. For a fixed OTTV/DA value, the peak electricity use variations can vary a great deal. For OTTV/DA = 150W/m² from the reference point (30W/m² OTTV and zero DA), $IPEU_A$ varies from about –3W/m^2 (peak load decrease) to over +15W/m^2 (peak load increase), depending on the different combinations of OTTV and DA values (i.e.

different building envelope designs). This indicates that OTTV/DA in itself is not a sufficient parameter to determine energy performance. Nevertheless, OTTV/DA can provide an indication of the likely energy efficiency and the optimum OTTV and DA (i.e. optimum WWR for a particular fenestration system used). For instance, with OTTV/DA = 150W/m², the optimum value can be determined by moving away from the reference point along the 'OTTV/DA = 150W/m² line'. Initially, the reduction in artificial lighting energy and its associated heat dissipation outweigh the increase in cooling requirement up to OTTV = 45W/m² and DA = 0.12. Beyond this optimum point, a reduction in electric lighting becomes progressively smaller and the cooling energy penalty begins to outweigh the natural daylight benefit. It can also be seen that for OTTV/DA ≥ 300W/m², peak load is always higher regardless of the building envelope designs, indicating that cooling penalty exceeds natural daylight benefits even though a daylighting design is used. The smaller the OTTV, the lower the energy penalty will be. For OTTV/DA ≤ 65W/m², there will always be peak electricity reductions with daylighting controls. A comparative energy performance study can also be conducted for different glass types. To illustrate this, the three types of glass commonly used in Hong Kong buildings are also shown in Figure 5.10. The relative energy performance of different fenestration design schemes can be assessed based on Figure 5.12. With a WWR of 0.5, reflective glass admits small amounts of solar heat and natural light. The DA is only 0.15 and the OTTV is just over 30W/m², resulting in about –10W/m² in $IPEU_A$. The DAs for clear glass and tinted glass are 0.43 and 0.25, respectively. A higher LT allows more daylight and hence less electricity use for artificial lighting and bigger reductions in sensible heat gain from electric lights compared with reflective glass. However, tinted glass and clear glass contribute higher OTTV values, which allow more solar heat to enter the interior spaces. The overall effects are that clear glass results in about 3W/m^2 more than tinted glass, which, in turn, is about 5W/m^2 more in $IPEU_A$ than reflective glass.

A similar approach can also be extended to develop contours of incremental peak cooling plant demand per building gross floor area ($IPCPD_A$) as a function of the OTTV and DA. Figure 5.13 presents the results. It appears that for a given OTTV and DA, the reduction in $IPCPD_A$ is not substantial and the drop is due mainly to the sensible heat dissipation generated by artificial light fittings. For example, negative $IPCPD_A$ values appear only at OTTV ≤ 50W/m² and DA ≥ 0.3 with daylighting controls. Again, the three types of glass (i.e. clear, tinted and reflective) with WWR of 0.5 are also plotted in Figure 5.13. It can be seen that although daylighting controls were used, a positive $IPCPD_A$ (i.e. overall $IPCPD_A$ increases) can be observed for both clear and tinted glass. This is because these two glazing types admit more solar heat gains and hence higher OTTV values. With daylighting controls, only reflective glass (OTTV = 32W/m²) can give less $IPCPD_A$ than the base-case building envelope design. The findings show that solar heat affects the OTTV determination significantly and hence dominates the trade-offs between daylight-induced energy saving and cooling penalty. Solar heat gain accounts for over 50% of the building envelope cooling load. For a building with a large window area and steady occupancy throughout the day (e.g. high-rise commercial buildings with curtain walls), the peak cooling demand is the time corresponding to the maximum solar heat gain (Clifford, 1990). Previous work (Li and Lam, 2000c) revealed that for 90% of the time, the solar heat gains are only half of their peak levels. This implies that effective elimination of the direct solar component can shift the time for peak cooling load and can decrease significantly the cooling plant capacity. Lighting controls combined with some advanced shading devices such as innovative automated blinds (Roche, 2002) or solar control film coatings, can efficiently cut down the amount of solar heat (the direct component) and hence the OTTV, achieving a smaller size and less HVAC equipment.

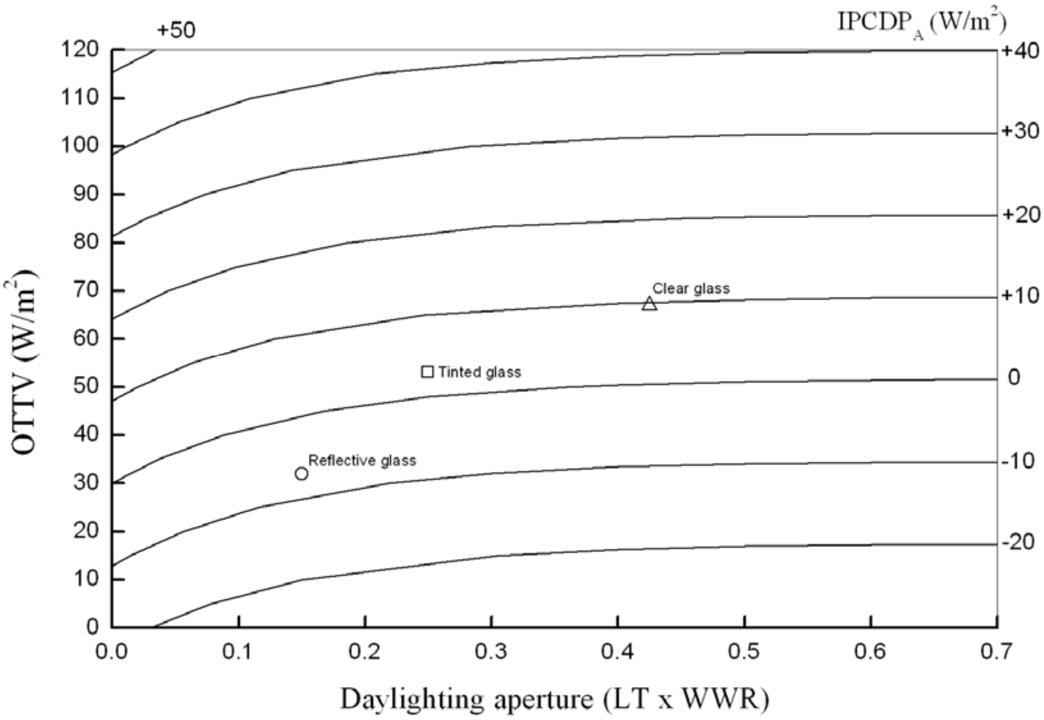


Figure 5.13 Contour of equal incremental peak cooling plant demand (○, reflective glass; □, tinted glass; Δ, clear glass)

5.5 Summary

The energy performance of a generic office building due to various daylighting schemes and different envelope designs was demonstrated. Using computer simulation technique, it was found that electricity consumption and peak loads could be reduced with the proper use of daylighting. Correlations between annual electricity expenditure and building envelope variables (in terms of OTTV and daylighting aperture) were conducted. The daylighting and energy performance in the four perimeter zones (north, east, south and west) were also analysed. The study was also extended to include the peak electrical demand and peak cooling plant demand. Both building electricity use and peak loads varied with OTTV and DA. Results from the regression analysis were used to develop sets of curves, which could indicate the incremental electricity use and peak loads under the combined impacts of OTTV and daylighting aperture. These composite diagrams could provide architects and building engineers a quick approach for assessing the energy performance of building envelope designs involving daylighting controls, especially during the initial conceptual design stage when different schemes are being considered.

The effects on air-conditioning plant and electrical equipment sizing were also illustrated when daylighting controls are involved. It has been shown that utilizing daylight control is an effective trade-off option to reduce cooling capacity and building energy use. The initial, running and maintenance costs of a building due to smaller HVAC plant capacity and peak electrical demand can be saved. The findings show that daylighting credits could be included in the current OTTV standard in Hong Kong and architectural designs would incorporate daylighting schemes to allow a more flexible building envelope design for building development. At a strategic level, the location of buildings should also be considered and the relative position of neighbouring buildings. It is common to find buildings severely over shaded by external obstructions in Hong Kong. In the next chapter, the shading effects due to nearby buildings and energy implications for buildings with daylighting controls will be analysed and presented.

Chapter 6 External Obstructions and Overall Energy Equations

6.1 General

Chapter 5 has established sets of curves, which could indicate the annual incremental electricity use, peak air-conditioning plant load and peak power demand reductions under the combined impacts of various building envelope parameters. Other than the building envelope designs, exterior elements (i.e. reflected light from nearby buildings and which shade the site from part of the sky due to obstructions) also play another significant role in daylight and energy analysis. In Hong Kong, most commercial buildings are high-rise constructions in densely built business districts and the shading effect from nearby buildings can be significant. This could restrict the quantity of daylight and solar heat penetrating into the building interior especially for rooms at the lower floors which rely very much on artificial lighting even in the daytime with high daylight intensity. Therefore, innovative daylighting technologies such as laser cut panel (Edmonds, 1993), light pipes (Chirarattananon et al., 2000) and anidolic light-duct (Courret et al., 1998) are appropriate devices to transport natural light from outside into deep plan rooms which are heavily obstructed. However, the lighting reflected from the ground (streets) and opposite facades can be also important sources of interior lighting (Tsangrassoulis and

Santamouris, 2003; Tsangrassoulis et al., 1999). Shading effect due to neighbouring buildings and structures depends very much on a large number of design features. By using computer simulation techniques, this chapter studies the building energy performance due to the shading effects from nearby buildings when daylighting schemes are considered. The energy impacts of external obstructions on the individual floors of office buildings are also discussed.

Among the building professions, it is generally accepted that building energy simulations are valuable design tools for the design and analysis of buildings and building services installations, particularly for large commercial developments. Discussions with architects and engineers, however, have revealed that most practitioners consider computer analysis techniques too complicated, time-consuming and costly (Lam et al., 1997). After establishing sets of energy curves for individual internal (i.e. building envelope designs) and external (i.e. shading effects) design elements of daylighting schemes, there is a need for some simplified approaches when different building design parameters are being considered together at the early design stage. This chapter also presents the work on the development of overall energy equations for the prediction of annual energy and peak electricity reductions of large fully air-conditioned office buildings using multiple regression techniques. It is envisaged that the developed energy models could be used by building designers as a simplified design tool for evaluating the relative energy performance of different daylighting schemes during the initial design stage.

6.2 Daylight and Obstructions

Being one of the fastest paced commercial cities in the world, Hong Kong is characterized by high-rise office building stocks. Most of the building blocks are 20 to 40 storeys high located in various business districts (Lam, 2000). Such developments, however, may result in quite a large degree of shading effect from nearby buildings. In subtropical regions, solar heat through fenestration on vertical surfaces plays a major role in determining the thermal performance of a building. It has been reported that in Hong Kong, solar heat gain accounts for over half of the total building envelope cooling load. However, for air-conditioning equipment sizing and analysis, it is customary to neglect the shading effect due to neighbouring buildings and structures. Moreover, based on computer energy simulation studies, Lam (2000) also pointed out that total building cooling load and annual building energy use would only be slightly overestimated if shading effect due to neighbouring buildings was not considered. Nevertheless, obstructing the sky will reduce the availability of natural light into the building and thus extend the operating hour of artificial illuminance, increasing lighting energy consumption.

6.2.1 Shading Effect

Local obstructions shade the site from direct sunlight at certain periods of the day and year. They will typically also obstruct parts of the sky vault and thus reduce the diffuse outdoor illumination levels as well. When placing a building at a site where severe obstructions exist next to the boundary, shading effect should be considered carefully. The relevant design parameter is the angle of obstruction from the window wall and this will vary for different floors of the building (Baker and Steemers, 2002) as will the view of the sky from different storeys as illustrated in Figure 6.1. Owing to the high level of obstructions, the view of the sky is very limited at the lower floors. This implies that less natural light will be received on the window glass. Therefore, excessive external obstructions to natural daylight from the sky can hinder the performance and effectiveness of a daylighting scheme. This has led building professionals to express a common desire for more information on the energy performance of buildings when daylighting schemes are adopted for commercial buildings affected by various degrees of sky obstruction.

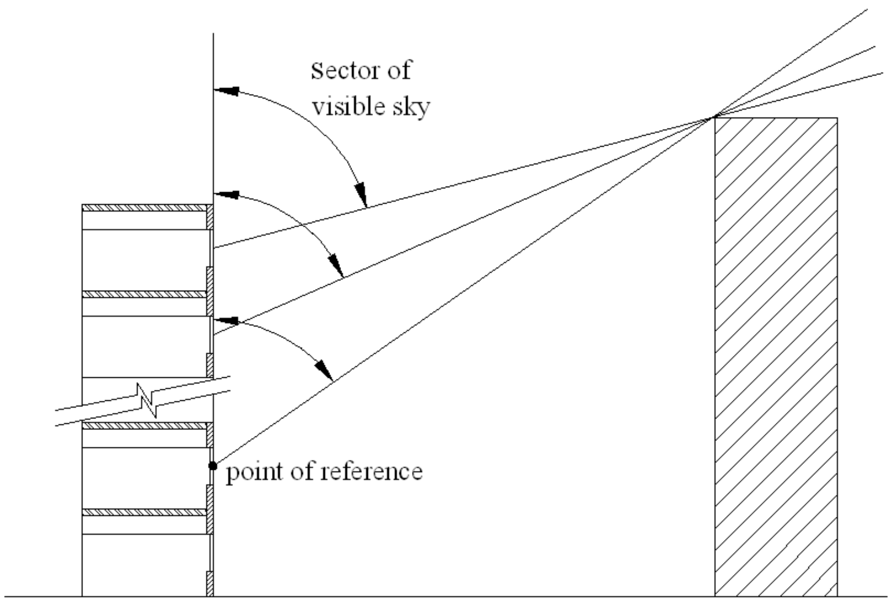


Figure 6.1 The sky view of different storeys due to obstruction

6.2.2 External Reflected Light

When considering the quantity of light falling on a reference point (i.e. daylight control point in a room or position at a window), three distinct components have to be accounted for. Light received directly from the sky is called the sky component (SkyC), which contributes a relatively high portion of natural light in the daylit zone. Light that is reflected from the internal surfaces is called the internally reflected component (IRC). The results in Chapter 4 show that building energy performances are not significantly influenced by modifying the reflectance of internal surfaces. However, the externally reflected component (ERC), which is the reflected light from external surfaces is particularly relevant in a dense urban environment (Baker and Steemers, 2002). ERC will penetrate deeper into the indoor space than the SkyC since it comes from a low angle, close to the horizontal for lower floors of highly obstructed buildings. Figure 6.2 shows the daylight at a reference point in a room coming from SkyC, ERC and IRC.

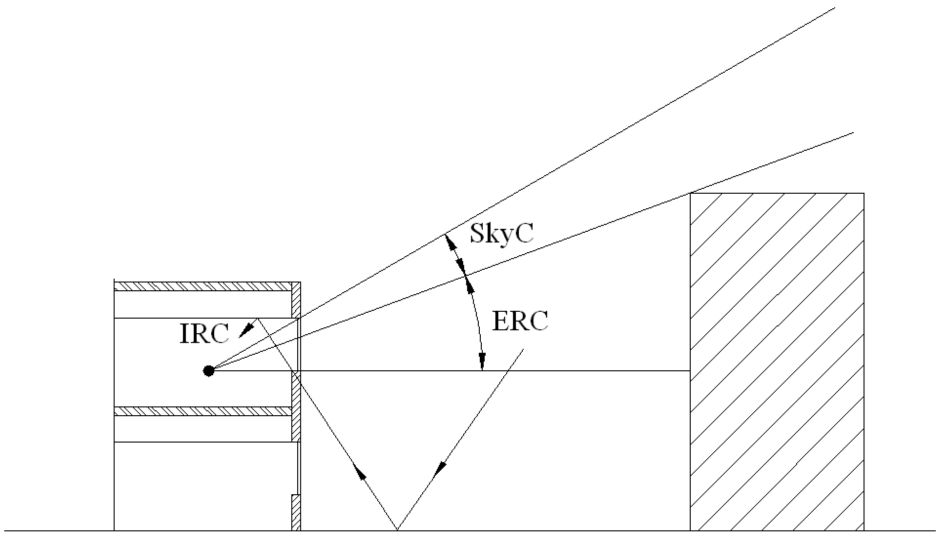


Figure 6.2 Three critical light sources at a reference point – SkyC, ERC and IRC

6.3 Shading Effect Analysis

The simulated findings will form a database, from which simple charts and diagrams can be used to assess the daylighting performance and building energy use of high-rise commercial buildings in Hong Kong facing in various orientations with external obstructions. It is envisaged that such correlation relationships and simple design tools can give architects and engineers certain basic and concise insights into the interdependency between building energy use and design parameters.

Analysis of the simulation results of the base-case model is very important because all subsequent calculations and analyses are based on the comparison with it. The base-case is the generic building with no shading effect (i.e. no external obstruction). The thermal and energy performance of the base-case generic office building is investigated in terms of total annual building electricity consumption.

6.3.1 Annual Electricity Consumption

Without daylighting control and heavy obstructions, the simulated annual electricity consumption of the building without daylighting controls is 9.8GWh. This represents an EUI of 200kWh/m^2, which is quite close to the office building without any obstructions (i.e. EUI of 204kWh/m^2 stated in Section 4.3.2 of Chapter 4). The annual building electricity consumption was broken down and is shown in Figure 6.3. The majority energy reduction comes from the air-conditioning systems, which account for only 2.9% of the total energy expenditure. It can be seen that air-conditioning energy requirements still dominate total energy expenditure, contributing around 40% total energy use. This also indicates the overwhelming importance of air conditioning in cooling-dominated commercial buildings in highly dense urban cities. As expected for reduction of solar radiation due to severe sky obstructions, the energy use in space heating is increased by about 45MWh. The electric loads of lighting and equipment account for 57% of total building consumption.

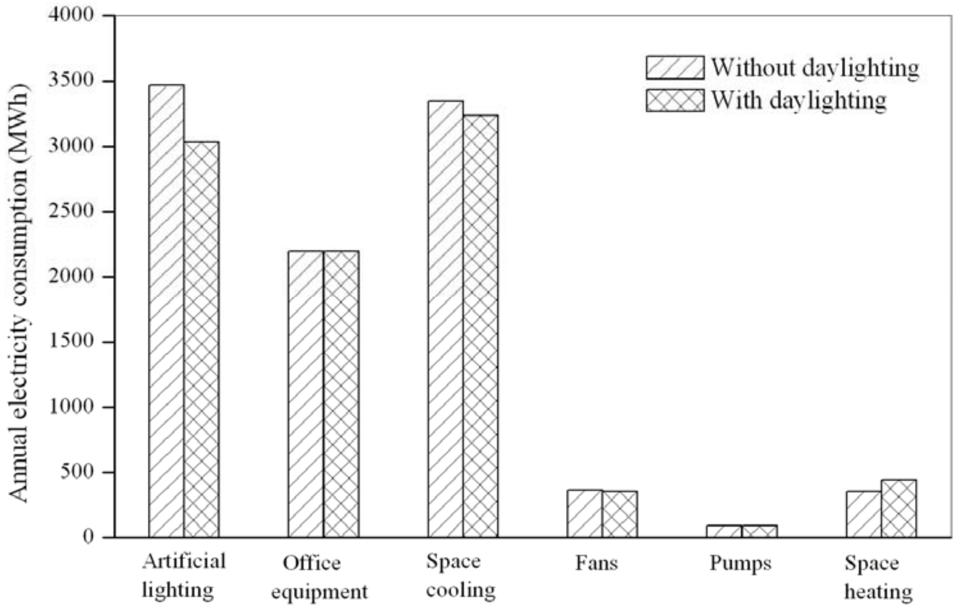


Figure 6.3 Breakdown of annual electricity consumption for a heavily obstructed (i.e. North: 40-storey building, East: 40-storey building, South: 40-storey building and West: 40-storey building) base-case generic office building with and without daylighting controls

With daylighting control and heavy obstructions, annual electricity consumption is lowered from 9.8 to 9.3GWh. The EUI is 191kWh/m², representing a 4.7% reduction. Annual lighting energy is also significantly decreased by around 433MWh, which is about 12% of the total building electric lighting use and corresponds to 4.4% of total building energy expenditure. The finding also represents a smaller but noticeable reduction of 3.2% in cooling energy resulting from less sensible heat gains generated by artificial lighting fittings. There is a slight increase in space heating, due mainly to a small drop in heat dissipation from electric lighting. The energy use for office equipment remains unchanged. Fans consume less amounts of electricity because of the lower peak load and part load conditions. Based on the computed results of Figures 4.11 and 6.3, the range of total energy savings of daylighting schemes from heavily obstructed to unobstructed external environments is 4.7% to 10%. This reveals that the application of daylighting controls is a remarkable energy conservation scheme in commercial developments.

6.3.2 Peak Electrical Consumption

Figure 6.4 shows the peak electrical demand of the generic office building with and without daylighting controls in a heavily obstructed situation. The peak electricity of the base-case building without daylighting controls is 4460kW, which accounts for energy reduction of about 2% for the building in an unobstructed environment (shown in Figure 4.12). With daylighting controls, the peak electricity consumption is about 50kW more than the case with external obstructions. It indicates that cooling energy reduction due to restricted solar heat gain is penalized by increased lighting load. Nevertheless, Figure 6.4 shows that daylighting design is still a key area for making substantial peak load reductions (around 7%) in cooling-dominated office buildings even in a densely built environment. However, in general practice, external obstructions are often not considered in peak load calculations for new building developments. Therefore, the peak load analysis of shading effect has not been further studied. It will only be involved in the development of the overall energy equations in Section 6.4.

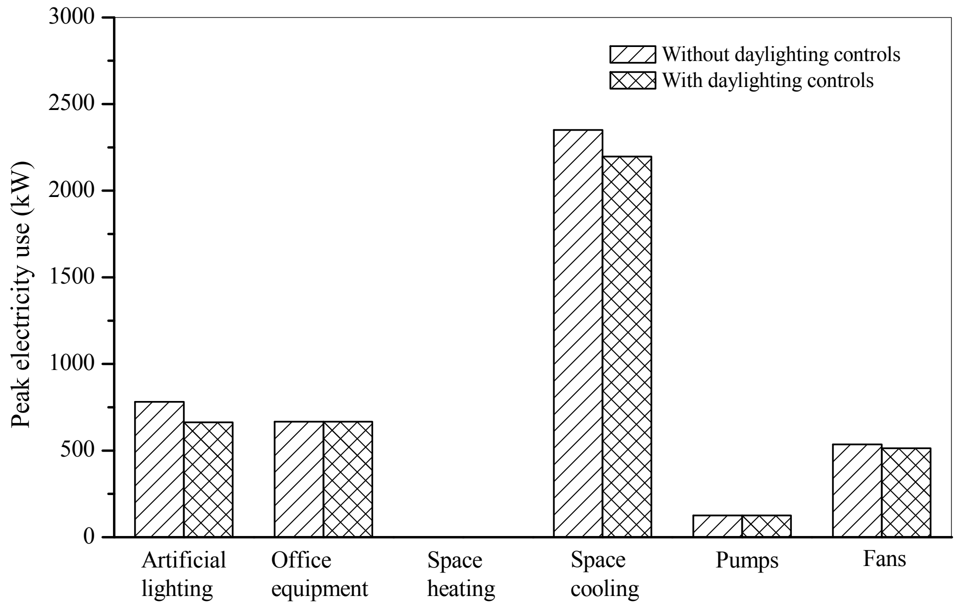


Figure 6.4 Breakdown of peak electricity consumption for a heavily obstructed (i.e. North: 40-storey building, East: 40-storey building, South: 40-storey building and West: 40-storey building) base-case generic office building with and without daylighting controls

6.3.3 Orientation Analysis

From the comparison of the energy performance between the two schemes (i.e. assuming with and without daylighting), it has been shown that daylight admitted through the building envelope offers an opportunity to significantly reduce lighting requirements and, to a lesser extent, cooling loads. The study, however, neglected the shading effect due to surrounding buildings (i.e. no sky obstruction). Without external obstruction, the reference building façade will be able to receive natural light from half of the sky hemisphere, contributing to large electric lighting and total building energy savings when dimming controls are used. The presence of a building nearby obstructs certain parts of the sky, and thus reduces the amount of daylight coming directly from the sky, resulting in less amounts of electric lighting energy savings. A detailed analysis of the shading effects from neighbouring buildings is, therefore, crucial to the development of proper daylighting schemes in Hong Kong. To facilitate an understanding of the shading effects, the obstructed areas of nearby buildings are often changed parametrically in computer simulations. Regression techniques are then used to study the shading effects due to external obstructions on the building energy consumption for the whole generic reference building as well as individual floors.

The Whole Building

External obstruction affects the building energy performance in two aspects. Shading effect will, on one hand, result in less cooling requirements due to a decrease in solar heat. It, however, will admit less amounts of natural daylight and increase electric lighting consumption with the associated cooling requirement under daylighting controls. To better understand the interactions, a series of simulations for the reference generic building was carried out with the orientation and area of the external obstruction being changed systematically. Since most useful light entering into building interiors comes from the sky normal to the glazing façade, it was assumed that the obstructing block of the same building length as the reference building was located in front of the reference generic building with a separation of 20m. The obstructing building with the floor-to-floor height of 3.5m (i.e. the same as the reference building) was varied, ranging from 35m (10 storeys) to 210m (60 storeys) at 35m (10-storey) intervals. Such simulations were conducted for four cardinal directions (i.e. N, E, S and W) to account for the orientation effects. In total, 25 simulation runs were conducted for the study (24 simulation runs with various external obstructions facing in the 4 cardinal orientations and 1 without external obstruction). Figure 6.5 is an example showing the external obstruction arrangement for the simulation. These 25 sets of simulation results were used for the subsequent regression analysis. To better understand the total building electricity savings, the incremental electricity reduction index due to daylighting and considering shading effect (i.e. the electricity consumption difference between the reference building with and without daylighting controls per floor area), $IEUI_S$, were computed and correlated with the angle between the roof of the reference and the obstructing buildings, measured parallel to the reference building façade, θ_B , as shown in Figure 6.6.

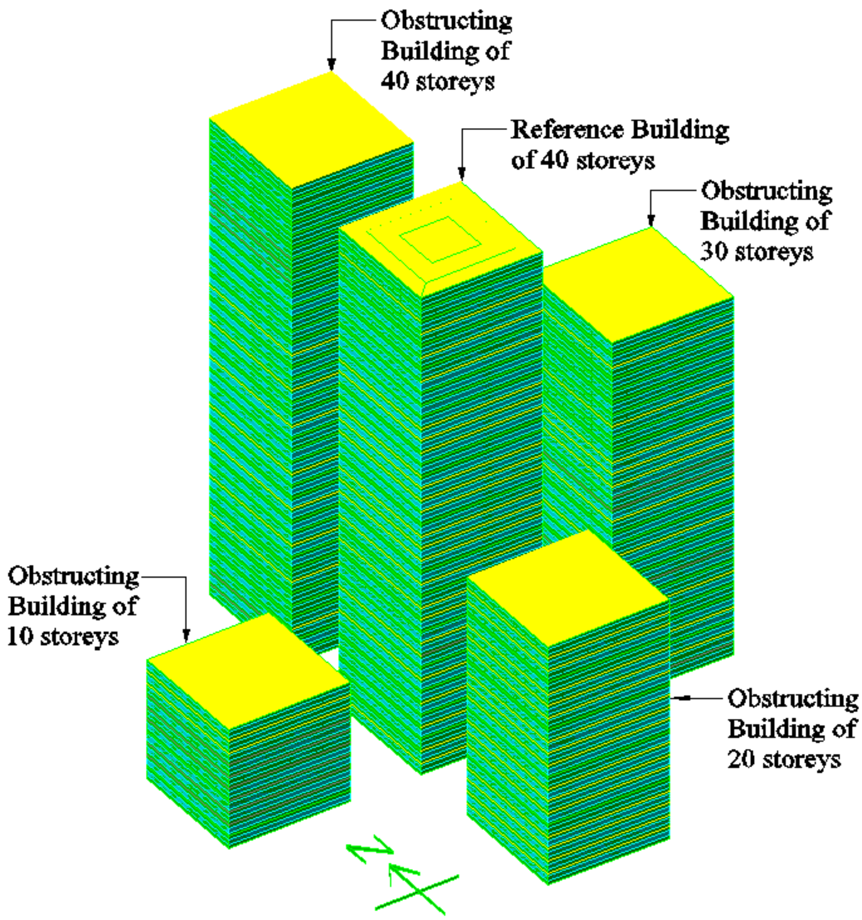


Figure 6.5 External obstruction arrangement for the simulation (e.g. North: 40-storey building, East: 30-storey building, South: 20-storey building and West: 10-storey building)

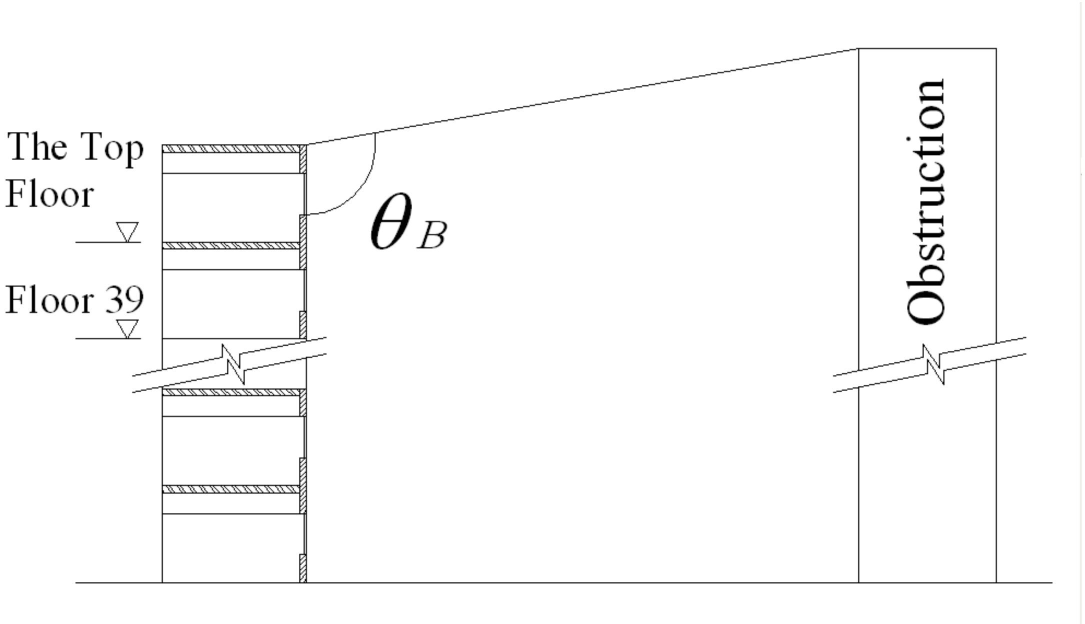


Figure 6.6 The angle between the façade of the reference building and the roof of the obstructing building, with the intersection of the roof and façade of the reference building as origin (θ_B)

As reported by Lam (2000), the shading effect due to neighbouring buildings on the total building energy budget would be very small if daylighting controls were not considered. For simplicity, the same building energy expenditure was assumed for various external obstruction environments when daylighting controls were not being used. Figure 6.7 plots the correlations between $IEUI_S$ and θ_B for the north perimeter zones. It can be seen that the peak electricity saving is 54kWh/m^2 when there is no external obstruction for the north perimeter zone. As the θ_B increases, there is a certain reduction in electricity use, indicating that the capacity of daylight to replace artificial lighting and reduction in heat dissipation from the electric lighting installation are high. However, as θ_B continues to rise, daylighting does not significantly contribute to additional building energy savings but degrades progressively. There are very small additional energy savings when θ_B is 90° or more (i.e. the obstructing building block is higher than the reference generic building). Similar features can be observed for other perimeter zones in Figures 6.8

to 6.10. Through regression analysis, the incremental $IEUI_S$ for the four zones can be correlated with θ_B as follows:

$IEUI_{S,N}$ (kWh/m²) = 31.1 $(1-e^{-0.0291\theta_B})$ -54 (6.1)
(north perimeter zone, R^2=0.973)

$IEUI_{S,E}$ (kWh/m²) = 29 $(1-e^{-0.0286\theta_B})$ -52.3 (6.2)
(east perimeter zone, R^2=0.972)

$IEUI_{S,S}$ (kWh/m² = 27.1 $(1-e^{-0.026\theta_B})$ -55 (6.3)
(south perimeter zone, R^2=0.968)

$IEUI_{S,W}$ (kWh/m²year) = 32.7 $(1-e^{-0.027\theta_B})$ -58.9 (6.4)
(west perimeter zone, R^2=0.971)

The R^2 for all four perimeter zones are close to 0.97, indicating that around 97% of the variations in $IEUI_S$ can be accounted for by the variations in θ_B. With such high R^2 values, the correlations for the four perimeter zones are considered strong.

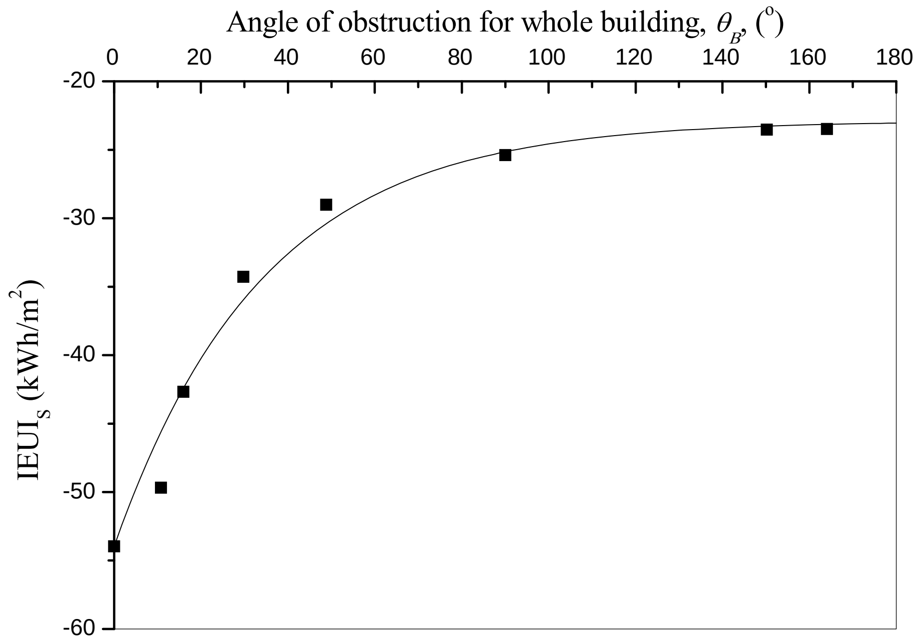


Figure 6.7 Correlation between the incremental electricity reduction index of the reference building ($IEUI_S$) and θ_B for the north perimeter zone

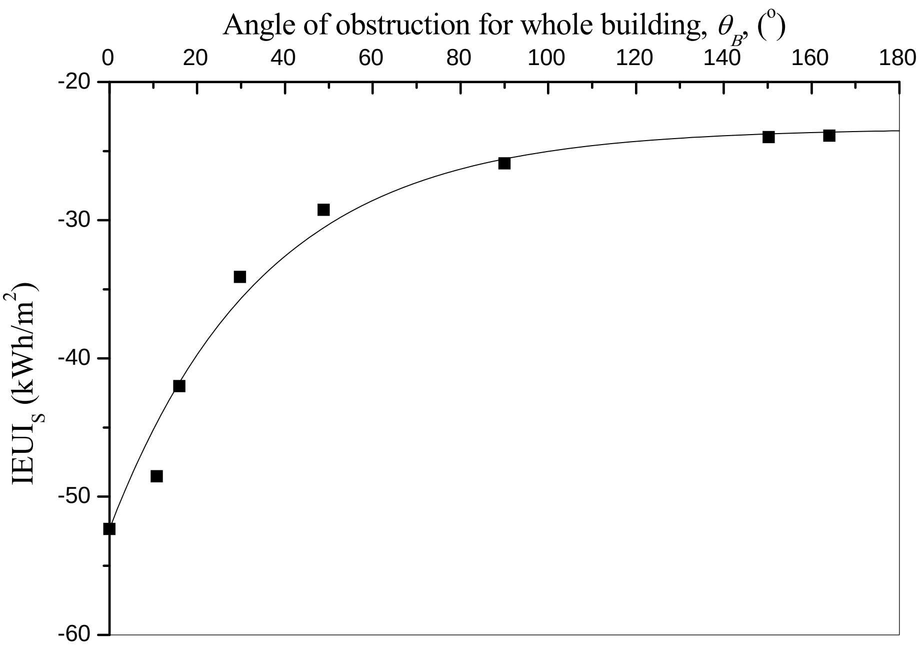


Figure 6.8 Correlation between the incremental electricity reduction index of the reference building (IEUI$_S$) and θ_B for the east perimeter zone

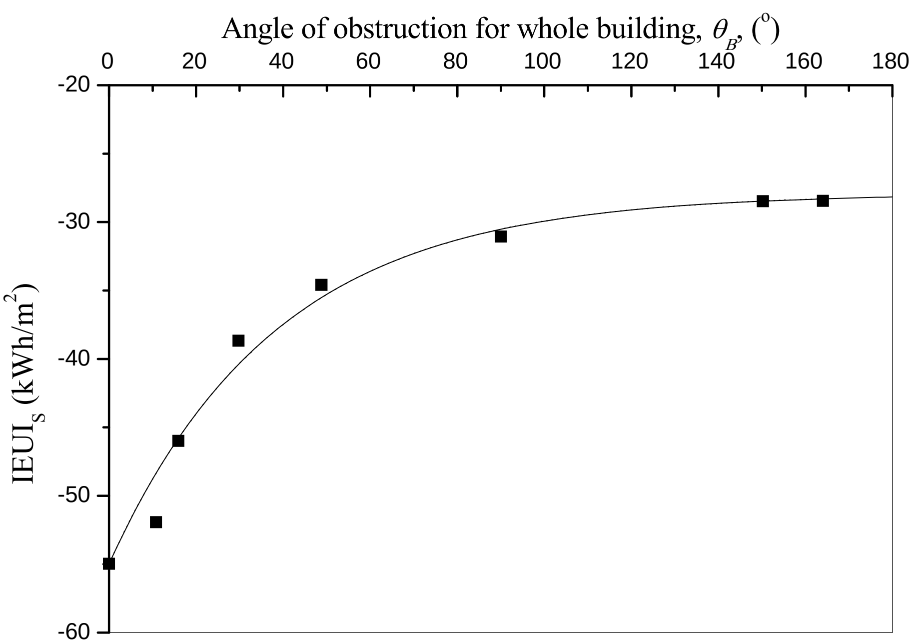


Figure 6.9 Correlation between the incremental electricity reduction index of the reference building (IEUI$_S$) and θ_B for the south perimeter zone

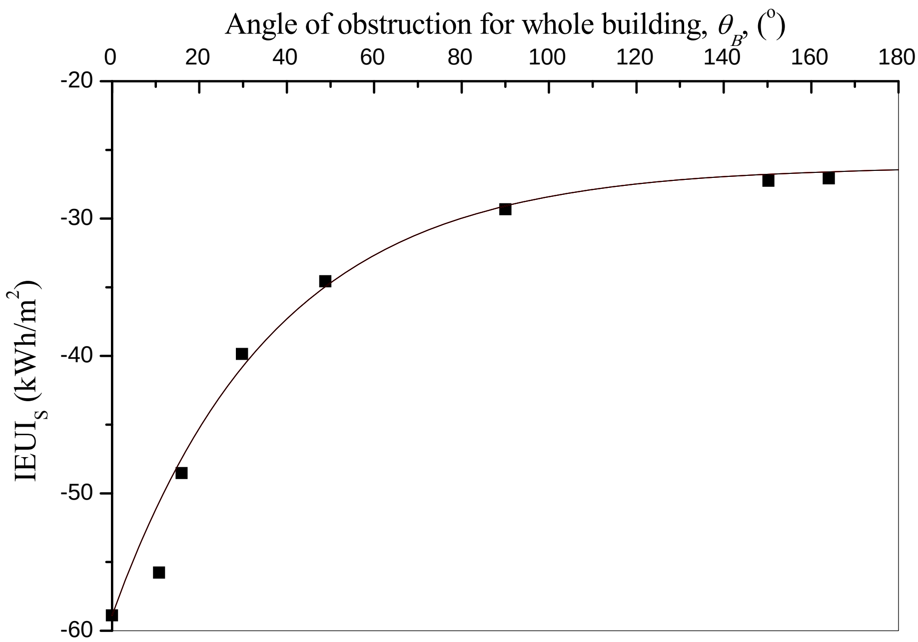


Figure 6.10 Correlation between the incremental electricity reduction index of the reference building ($IEUI_S$) and θ for the west perimeter zone

Individual Floor

Further analysis can also be extended to study the incremental electricity reduction index due to daylighting and considering shading effect for each floor ($IEUI_{S,F}$). For those floors not blocked by nearby buildings, the same peak energy savings were computed. The angle of obstruction (ϕ) is measured from the window sill above the horizontal of individual storeys (shown in Figure 6.11), which can accurately represent the quantity of outdoor illuminance that will be received on the window in a heavily obstructed environment (Li et al., 2006b).

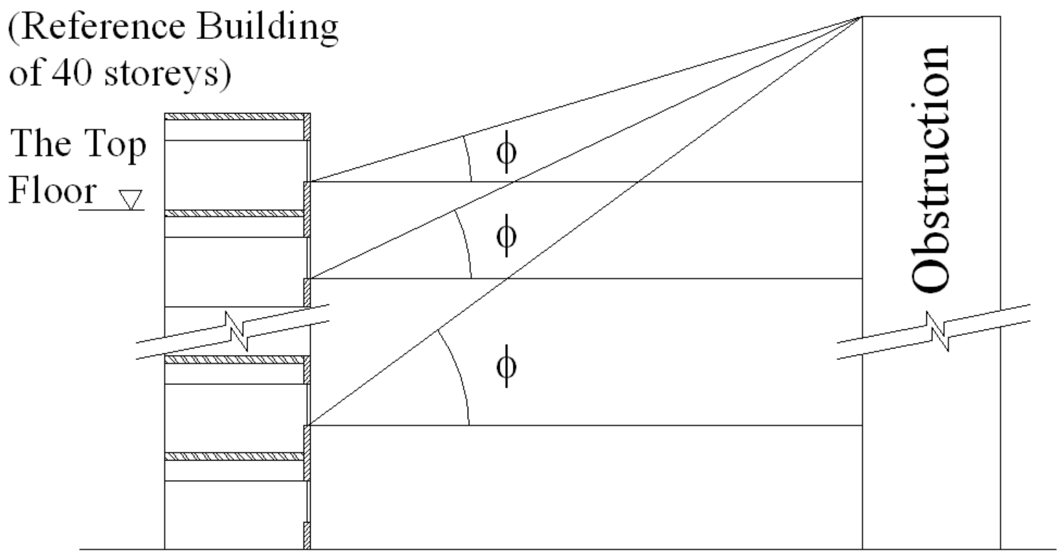


Figure 6.11 The angle between window sill for individual floors and the obstructing block (ϕ)

Figures 6.12 presents the variations of $IEUI_{S,F}$ with respect to ϕ for the north perimeter zone. Again, a peak energy saving of 54kWh/m² appears at $\phi = 0°$ for the north perimeter zone when there is no obstruction or the obstruction is below the reference window sill. At small values of ϕ, artificial lighting is significantly displaced by daylight, indicating that the capacity of daylight to replace artificial lighting is high. As the obstructing buildings were varied for the simulation, individual floors (i.e. different floor levels) with the same ϕ may have different values of $IEUI_{S,F}$. Such discrepancies which may be due to the ground reflection effect cause noise in the calculated points. As ϕ increases, the shading effect becomes severe and causes smaller amounts of electricity savings. It can be observed that the $IEUI_{S,F}$ decreases from 45 to 28kWh/m² when ϕ changes between 25 and 30°. It seems that $\phi = 30°$ is the critical value for daylighting design. Thereafter, the $IEUI_{S,F}$ reduces slightly and remains almost unchanged when ϕ is beyond 70°. When a nearby building with a similar height to the building of interest is razed and replaced by a much taller one, the $IEUI_{S,F}$ for the topmost floors drops gently and $IEUI_{S,F}$ for lower floors remains almost constant at 25kWh/m^2. Regression analysis has suggested that $IEUI_{S,F}$ can be expressed as a fourth degree polynomial function of ϕ for the north perimeter zone as:

$$IEUI_{S,FN}\ (kWh/m^2) = -54 - 0.1114\phi + 0.0393\phi^2 - 0.00083\phi^3 + 4.81\times10^{-6}\phi^4 \quad (6.5)$$
(R^2=0.983)

The R^2 value is 0.983, representing that just over 98.3% of the $IEU_{S,F}$ variations can be explained by the variations in ϕ. Similar features for the other three perimeter zones were found and are shown in Figures 6.13 to 6.15. Through regression analysis, the equations for the other three perimeter zones are given as:

$$IEUI_{S,FE}\ (kWh/m^2) = -52.3 - 0.1406\phi + 0.0259\phi^2 - 0.00047\phi^3 + 2.23\times10^{-6}\phi^4 \quad (6.6)$$
(east perimeter zone, R^2=0.985)

$$IEUI_{S,FS}\ (kWh/m^2) = -55 - 0.0448\phi + 0.025\phi^2 - 0.00044\phi^3 + 2.19\times10^{-6}\phi^4 \quad (6.7)$$
(south perimeter zone, R^2=0.987)

$$IEUI_{S,FW}\ (kWh/m^2) = -59.8 - 0.1024\phi + 0.0314\phi^2 - 0.00056\phi^3 + 2.66\times10^{-6}\phi^4 \quad (6.8)$$
(west perimeter zone, R^2=0.981)

All of the R^2 values for the four cardinal orientations exceed 0.98, indicating a strong correlation between $IEUI_{S,F}$ and ϕ.

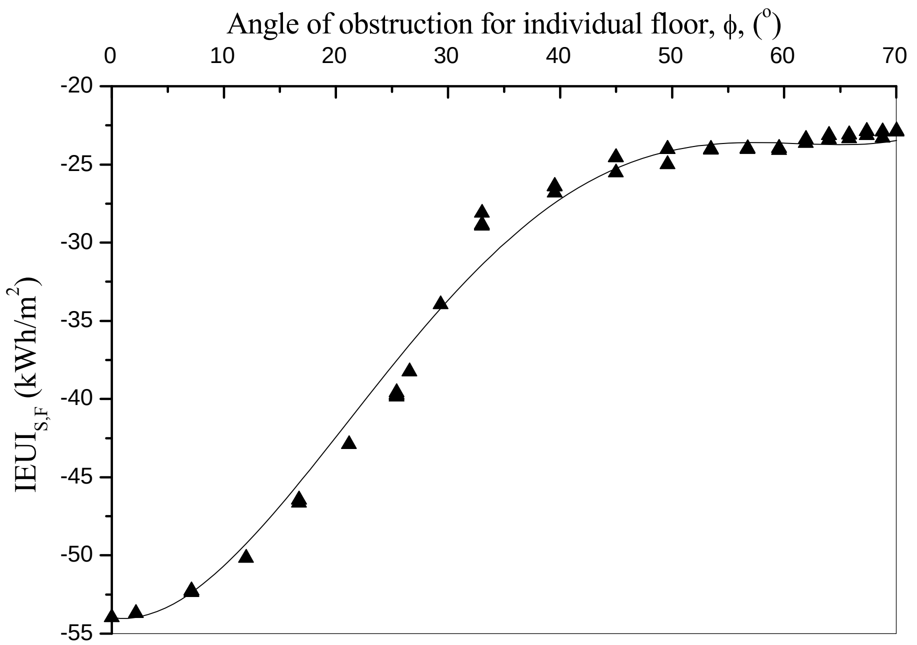


Figure 6.12 Correlation between the incremental electricity reduction index for individual floors ($IEUI_{S,F}$) and ϕ for the north perimeter zone

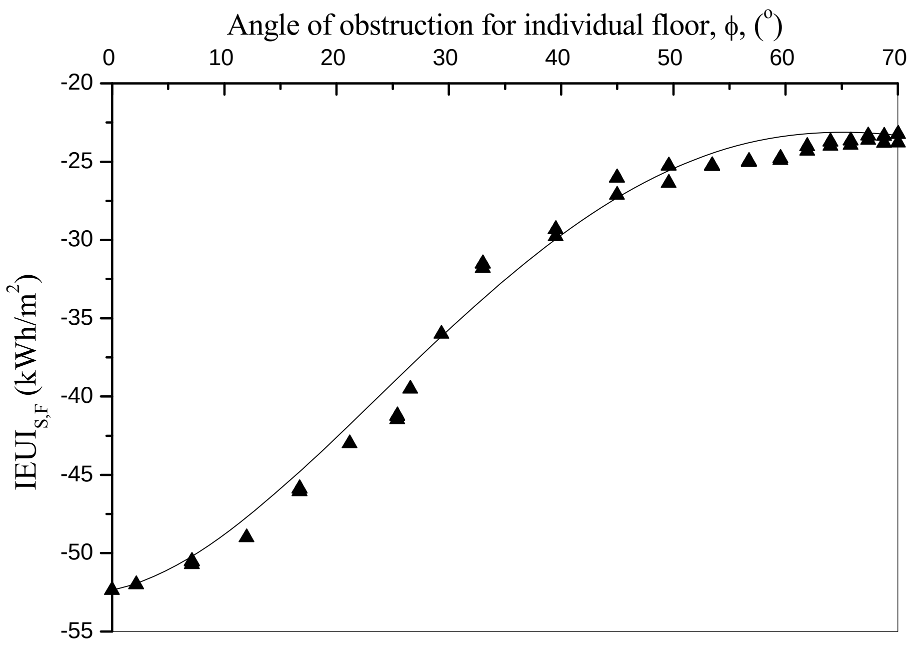


Figure 6.13 Correlation between the incremental electricity reduction index for individual floors ($IEUI_{S,F}$) and ϕ for the east perimeter zone

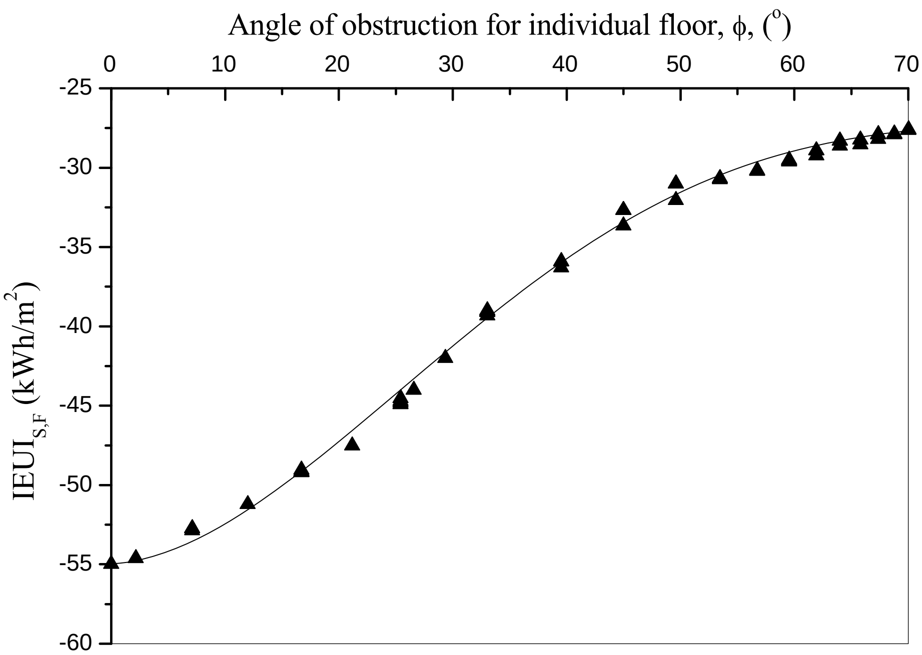


Figure 6.14 Correlation between the incremental electricity reduction index for individual floors ($IEUI_{S,F}$) and ϕ for the south perimeter zone

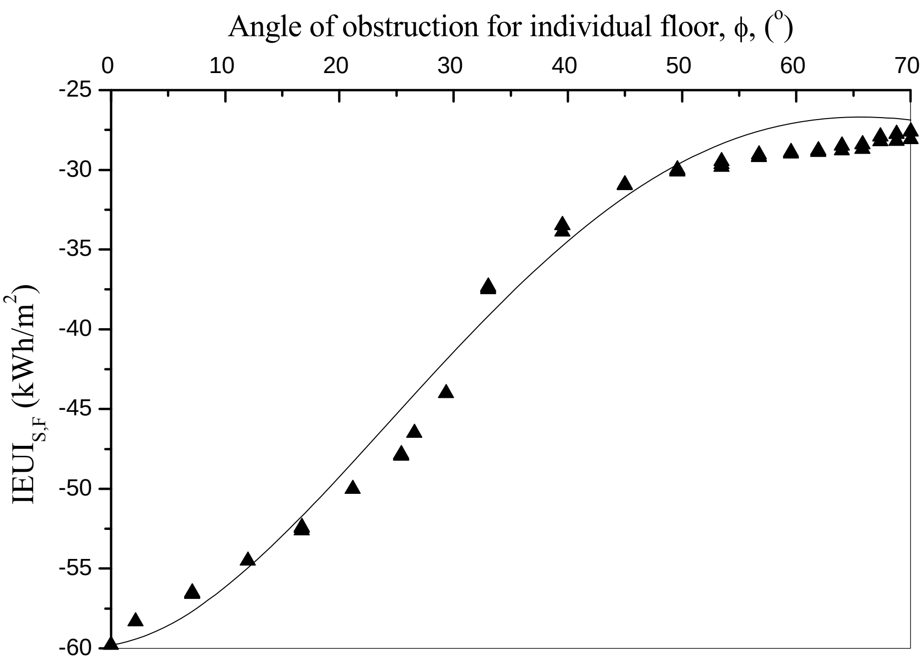


Figure 6.15 Correlation between the incremental electricity reduction index for individual floors ($IEUI_{S,F}$) and ϕ for the west perimeter zone

Comparative Study

To assess whether the regression equations are applicable to various sky obstructions, the building energy savings estimated by the regression models were compared against other independent results. The independent simulation run with various degrees of shading effect for different orientations was conducted to generate data for the assessment. In this connection, obstructing buildings of 15-storey (52.5m), 25-storey (87.5m), 35-storey (122.5m) and 45-storey (157.5m) located, respectively, to the north, east, south and west of the reference building were assumed. Again, the EnergyPlus software was used for the simulation. The simulated and predicted $IEUI_S$ were computed to be 36.1 and 38.8kWh/m^2, respectively. The difference is 2.7kWh/m^2, which represents about 7.5% of the simulated $IEUI_S$ value. It shows that using the proposed prediction equations can obtain similar simulated results. A comparative evaluation of the prediction models for individual floors was also conducted. Figure 6.16 displays the simulated and estimated $IEUI_{S,F}$ for each floor of the reference building. The discrepancies in the simulated and predicted values range from 0.006 to 2.1kWh/m^2. The MBE and RMSE of the $IEUI_{S,F}$ were determined to be 0.3 and 0.9kWh/m^2 representing 0.8 and 2.6% of the simulated mean value. It should be pointed out that overestimation for individual perimeter zones can be offset by the underestimation for the other perimeter zones of the same floor contributing to small discrepancies. In general, the differences between simulated and predicted $IEUI_{S,F}$ are small.

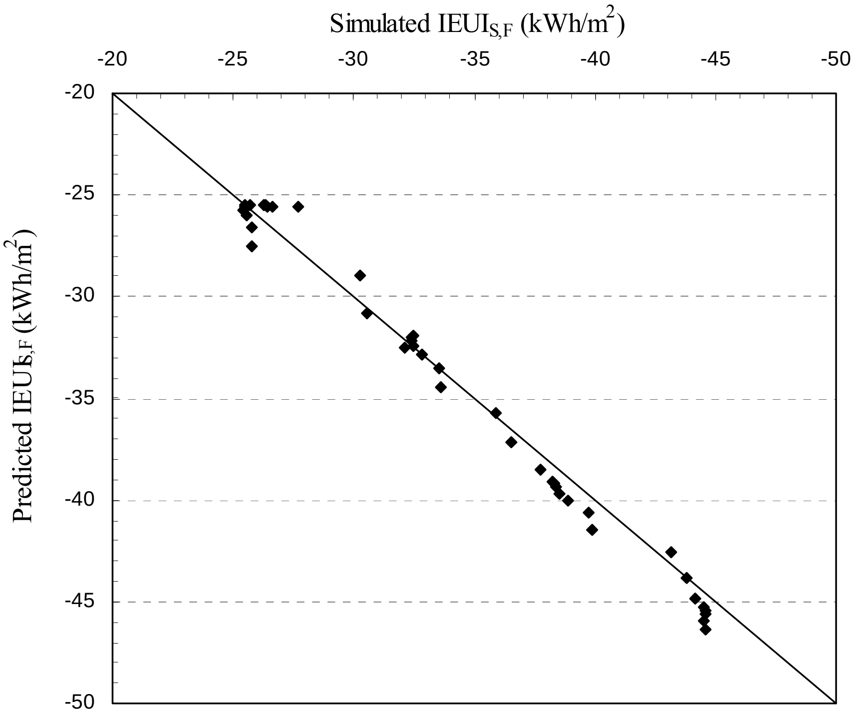


Figure 6.16 Simulated and estimated incremental electricity reduction for individual floors ($IEUI_{S,F}$)

6.4 Energy Reduction Index

For energy saving analysis of daylighting, Chapter 5 and the previous section developed a set of regression equations for individual design parameters of building envelope design and external obstruction. If the regression equations are extended to include all the design parameters, a set of energy equations can be developed as an effective means for analysing building energy performance (Lam et al., 1997; Kim and Kim, 2007b) and daylighting analysis (Huang et al., 1989).

Before carrying out the multiple regression analysis, design variables should be selected. In Hong Kong, the code of practice for OTTV limits the building envelope cooling load and controls building facade designs. In this regard, the four building envelope parameters, namely WWR, LT, OV and SF are further investigated to form the building energy regression models. It should be pointed out that the SC and LT are the two important interrelated properties for window glazing. Practically, both SC and LT will be varied according to various typical glazing types though the SC will not be used to form the regression models. Another crucial design consideration for daylighting, i.e. shading effect, was also considered in the energy models. Different heights (i.e. in terms of θ_B) of obstructions were built on the four cardinal orientations (i.e. N, E, S and W) of the reference office building for the regression analysis.

6.4.1 Multiple Regression Models

If the parameters of envelope design and external obstruction are considered together as the functions, the general forms of energy equation (or energy reduction index) for incremental annual energy use and incremental peak electricity use for daylighting schemes were set as a simple form as follows:

$$E_{IEUI}\ (kWh/m^2) = f(WWR, LT, OV, SF, \theta_N, \theta_E, \theta_S, \theta_W) \quad (6.9)$$

$$E_{IPEUI}\ (W/m^2) = f(WWR, LT, OV, SF, \theta_N, \theta_E, \theta_S, \theta_W) \quad (6.10)$$

where E_{IEU} = annual energy reduction index (kWh/m^2)

E_{IPEU} = peak electricity reduction index (W/m^2)

θ_N = angle of obstruction at north of whole building (º)

θ_E = angle of obstruction at east of whole building (º)

θ_S = angle of obstruction at south of whole building (º)

θ_W = angle of obstruction at west of whole building (º)

Regression techniques using the statistics package SPSS (Norusis, 2005) were employed for the multiple regression analysis. The statistical methods use the least-square approach to find the best fit to the data. The 'goodness of fit' of the model is measured by the R^2, which is equal to unity if a perfect fit is found. The standard error, which is the standard deviation of the residuals of the regression model, can be used to draw statistical inferences about the model performance. The simplest formula for expressing the above functions will involve adding of the group functions. In order to get a better regression fit, it is necessary to add new variables into the equation by combining some parameters (i.e. a product term of two parameters) (Hui, 1996). Daylight aperture (LT × WWR) was selected as a new term in the regression analysis since it is well correlated with the IEU and IPEU and has significant influence on daylighting as found in Chapter 5.

When the number of variables is large, an enormous amount of computer simulations will be performed to create data input for the regression analysis. The total number of simulations for all combinations of the perturbations of the design parameters may be unacceptably large. For example, if there are eight parameters and each of them require three perturbation values, then the total number of simulations required for all combinations of them is equal to three to the eighth power (3^8) times two (i.e. a reference building incorporated with daylighting and without daylighting schemes), i.e. 6,561 × 2 simulations. To tackle this problem, the perturbation was only performed for the building envelope design parameters. Table 6.1 shows the perturbation values of the envelope design parameters used for the simulations. The twelve simulation results presented in Chapter 4 and twenty-eight simulation results in the previous section for the shading effect analysis were also adopted for the regression analysis. Therefore, a total of two hundred and two (202) simulation results were used to develop the energy equations. Generally speaking, the more cases that are simulated, the more representative the regression model will be. However, it is difficult to determine the minimum number required for every situation, unless a feedback mechanism can be installed in the simulation cycle to check for the necessity of including more cases. Due to time-consuming simulation processes for each case, the 202 simulation cases are considered sufficient and efficient to apply in the regression analysis.

TABLE 6.1 Perturbation values for multiple regression analysis

Envelope parameters	WWR	LT	OV	SF
(3^4 x 2 = 162 runs)	0.1	0.1	0	0
	0.5	0.5	0.2	0.2
	0.9	0.9	0.4	0.4

Values for the IEU and IPEU of different design options were extracted from the simulated results and sent to the SPSS statistics package to conduct the multiple regression analysis. To correlate with E_{IEUI} and E_{IPEUI}, linear and non-linear regression models were used in developing the energy equations for the eight parameters. The developed energy equations for daylighting design are as follows:

$$E_{IEUI}\ (\text{kWh/m}^2) = 12.2 - 98.3WWR^3 + 161.8WWR^2 - 81.5WWR + 11.2WWR \times LT - 129.5LT^3 + 214.7LT^2 - 122.6LT + 5.2OV + 3.9FN + 0.066\theta_N + 0.062\theta_E + 0.05\theta_S + 0.058\theta_W \quad (6.11)$$

(R^2 = 0.968, standard error = 1.15 kWh/m^2)

$$E_{IPEUI}\ (W/m^2) = 5.54 - 92.5WWR^3 + 170.6WWR^2 - 82WWR - 18.5WWR \times LT - 22.1LT^3 + 35.7LT^2 - 15.6LT + 0.54OV + 0.26FN + 0.008\theta_N + 0.008\theta_E + 0.007\theta_S + 0.007\theta_W \quad (6.12)$$

(R^2 = 0.975, standard error = 0.65 W/m^2)

The R^2 for Equations. 6.11 and 6.12 are more than 0.96, indicating that more than 96% of the variations in IEU and IPEU can be explained by the variations in the eight input variables. These equations can be used to assess the effect of the daylighting designs on building energy performance.

6.4.2 Comparative Study

To evaluate whether the regression equations are applicable to various input values, the E_{IEUI} and E_{IPEUI} estimated by the regression models were compared with other independent results. Another 32 random simulation runs (16 without daylighting and 16 with daylighting) were conducted for the two regression models to generate the test data. Figures 6.17 and 6.18 present the comparisons of E_{IEUI} and E_{IPEUI} generated from the simulations to those estimated from the energy models. It can be seen that regression models are quite good in predicting the energy consumption and peak demand for various sets of randomized results. To further assess the accuracy of the regression models as compared with those simulated results, MBE and RMSE were determined. The calculated MBEs for E_{IEUI} and E_{IPEUI} are 0.22kWh/m^2 and -0.06W/m^2, respectively. These stand for -1.25 and 0.63% of their corresponding mean simulated E_{IEUI} and E_{IPEUI} values. The RMSEs for E_{IEUI} and E_{IPEUI} are 1.18kWh/m^2 and 1.04W/m^2, respectively, representing 6.57 and 10.75% of the mean E_{IEUI} and E_{IPEUI} from the simulations. In general, the

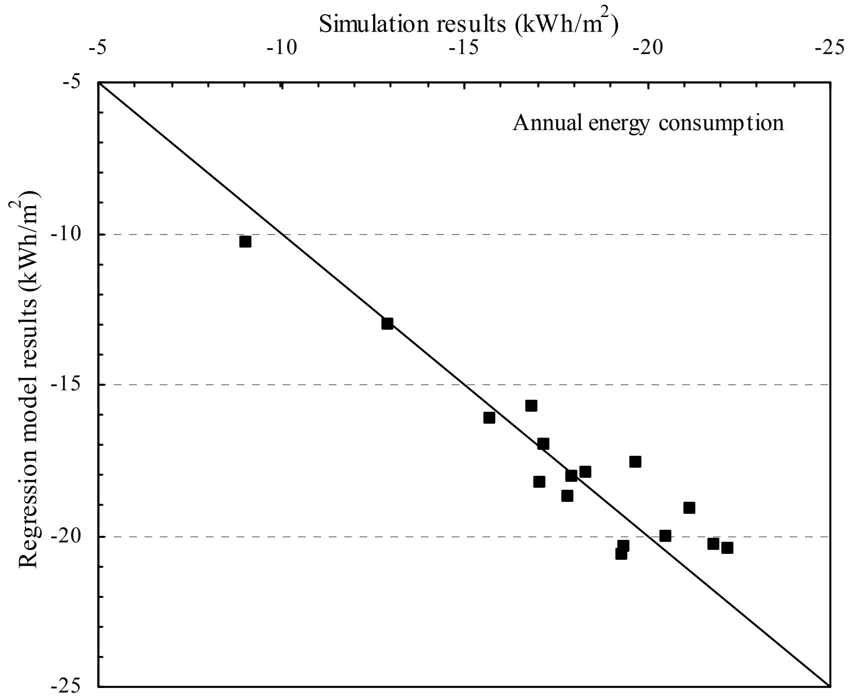


Figure 6.17 Comparison between simulated and estimated annual energy reduction index (E_{IEUI})

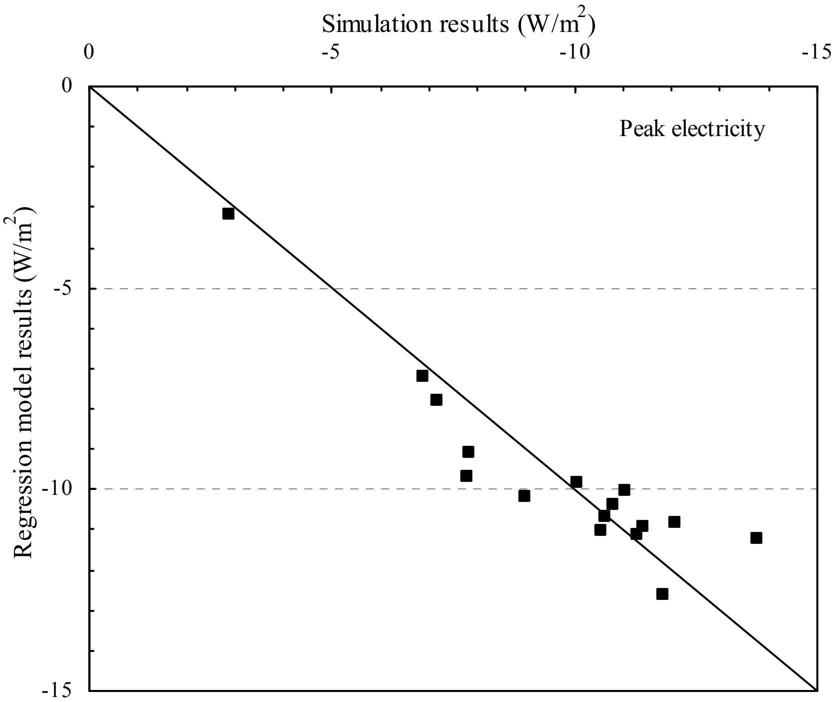


Figure 6.18 Comparison between simulated and estimated peak electricity reduction index (E_{IPEUI})

differences between simulated and predicted E_{IEUI} and E_{IPEUI} are not large. It indicates that Equations 6.11 and 6.12 can be used efficiently to determine the building performance during the initial design stage when various daylighting design schemes are being considered and evaluated.

6.5 Summary

A procedure involving computer simulation techniques was employed to evaluate the energy performance for office buildings with daylighting controls shaded by neighbouring buildings. A detailed study of the shading effects showed that daylighting is always an energy saver. Results from the regression analysis were used to establish a number of correlation equations, which could indicate the energy savings under the impact of external obstruction. The substantial electricity energy reductions of 25 to 28kWh/m² for the various perimeter zones were found even the reference building was heavily obstructed. It reveals that reflected light from external surfaces can provide a certain amount of daylight at lower floors of building. It was also found that the electricity savings decreased substantially when the angle of obstruction of the individual floors varied between 25 and 30°.

To establish an energy reduction index and energy target due to various daylighting schemes, the multiple regression technique was used. It demonstrates the accuracy of an approach to expressing energy saving potentials of daylighting in terms of a number of design variables which will be considered critical in the early design stage for new commercial buildings. A simplified and flexible method is proposed which offers the feasibility of developing design criteria for energy prediction that can extend beyond the local building energy codes. It is also believed that the established energy equations for daylighting designs can be integrated into performance-based energy analysis to assist designers in assessing building energy performance effectively. In Chapter 7, the lighting and cooling energy performances for a fully air-conditioned open-plan office are studied when advanced solar control films together with daylight-linked lighting controls are used. The findings are extended for use in the analysis of energy performance for existing office buildings.

Chapter 7 Daylight and Energy Performance of Solar Film Coating

7.1 General

Besides implementing energy conservation designs for new commercial buildings, existing buildings are also going to be considered for their energy efficiency performance when they are undergoing major renovations. High–rise office buildings (20 storeys or higher) were built in Hong Kong during the 1980s. Most buildings constructed in that period tended to have larger windows with tinted glass (Lam et al., 2004). Daylighting is still a feasible scheme to reduce energy consumption of these buildings. However, the benefits from daylight may be negated by the corresponding high transmitted solar radiation. Moreover, owing to the small angle of incidence, direct sunlight can be excessive for east-facing windows in the early morning and west-facing windows in the late afternoon. In Hong Kong, external shading devices were not popular because many large scale prestigious building projects in up-market commercial districts had a tendency to use curtain walling. 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 when daylight linked-lighting controls are used (Li et al., 2004). Recent advances in solar film coatings for window glass products provide a means of substantial solar heat reduction due to the direct beam and diffuse components. It indicates that the energy expenditure due to lighting and cooling requirements can be minimized, while people can enjoy natural light and maintain good visual contact with the outside environment.

The objective of this chapter is to evaluate the daylighting performance and energy issues for existing office buildings when considering solar film coatings together with high frequency dimming controls as an energy conservation scheme in renovations. Analysis of the energy performance of daylight-linked dimming controls via field measurements can provide important information for various daylighting schemes (Atif and Galasiu, 2003; Kim and Mistrick, 2001; Kim and Kim, 2007a). These energy measures were incorporated into an open-plan office, in which daylight illuminance, solar radiation, electric lighting use and cooling energy consumption were systematically recorded and analysed. A reference building of the 80s' design features was further modelled in a business district, Wan Chai, in Hong Kong. The measured optical properties of the solar film coatings were input into the computer software, EnergyPlus, to demonstrate the likely annual electricity use, peak air-conditioning load and electrical demand reductions for the building. The results will be extended to provide the thermal and visual aspects contributed by solar control film exploited in different building envelope designs.

7.2 Solar and Visible Performance

To get the likely solar and visible performance for the solar control films, simultaneous measurements for solar radiation and daylight illuminance were conducted in two open-plan office spaces (one with and the other without using solar control films). The two identical offices were next to each other and facing in the same orientation with similar external environments. One of the offices was reused to install solar film coatings on the windows after conducting the measurement of daylighting performance that is reported in Chapter 4. The room characteristics and building services installations are already described in Section 4.2. An additional set of pyranometers was installed to measure the penetrating solar radiation of the windows. Two pyranometers manufactured and calibrated by Kipp and Zonen, the Netherlands, were used to record simultaneously the solar radiation for the open-plan offices with and without solar control films on the windows.

As the two interior spaces were fully air-conditioned with the windows completely closed all the time, only transmitted solar radiation and daylight illuminance data were logged. The pyranometers (CM11) with an accuracy of ±3% were connected to an integrator recording the solar radiation at an interval of 10 minutes. Similarly, the transmitted daylight illuminances through windows with and without solar control films were recorded by two illuminance meters (T-10). Due to some administrative constraints, the power analyzer (43B) was only installed in the office of solar control films to conduct the measurement of electric lighting energy consumption. The chilled water flow rate and supply and return temperatures were also recorded to estimate the cooling load requirements of the office.

7.2.1 Solar Radiation and Daylight Illuminance Profiles

In September 2004, the field measurements were carried out to determine the electric lighting and cooling energy expenditure for the open-plan office using a simple photoelectric dimming system together with solar control film coatings. There was a major interruption between January and March 2005 for the water flow sensors. The cooling energy study, therefore, excluded these three heating months. In total, 12 months (September 2004 and August 2005) daylight availability and electric lighting energy data and 15 months (from September to December 2004 and from April to August 2005) cooling energy readings were analyzed. The recorded results were compared with the daylight and energy performance of the office, which was not covered with solar film coatings between March 2004 and August 2004.

To get an idea of the solar and visible performance for the solar control films, simultaneous measurements for solar radiation and daylight illuminance in the two identical offices were conducted. Due to the site restriction, such field measurements were made in July 2005 for a few days. It is very difficult to set outside measurements for a fully air-conditioned office and the global vertical irradiance and illuminance inside were recorded. The graphical comparisons can indicate the performance of the solar film coatings in terms of solar radiation and daylight illuminance reductions. Figure 7.1 shows the daily measured solar radiation profiles for the two offices for a specific day. It can be observed that the curves have an almost identical trend and peak at the same time indicating that similar amounts of solar radiation fell onto the window facades of the two rooms during the measurement periods. The coated windows do reduce the solar heat entering the interior spaces particularly when the solar radiation consists of a certain amount of direct component. With the film coatings, the measured maximum hourly solar radiation of 160Wh/m^2 decreased to 112Wh/m^2, representing a reduction of over 30%. Similar patterns were found for other days. A previous study however revealed a solar heat reduction of over 50% in summer afternoons for west-facing (270°) windows coated with the solar control films (Li et al., 2004). The less solar heat reduction obtained for the present case may be due to the smaller amount of direct beam solar radiation received during the measurements. In subtropical Hong Kong, solar heat gain via fenestration contributes about 17% of total building cooling load of air-conditioned office buildings (Li et al., 2002a). The cooling energy may not always be substantially reduced using the solar film coatings. Nevertheless, solar control films can effectively lower the thermal discomfort and peak solar heat gain when the solar radiation contains large amounts of direct component. Likewise, the daily daylight illuminance profile for another day is plotted in Figure 7.2. Using the solar control films, the reduction in visible transmittance is quite constant. The peak daylight illuminance of 16.5 klux at 17:00 was reduced to around 9.2 klux, accounting for a reduction of over 40%. The reduction is substantial but this implies that less electric lighting energy is saved when solar film coatings are used.

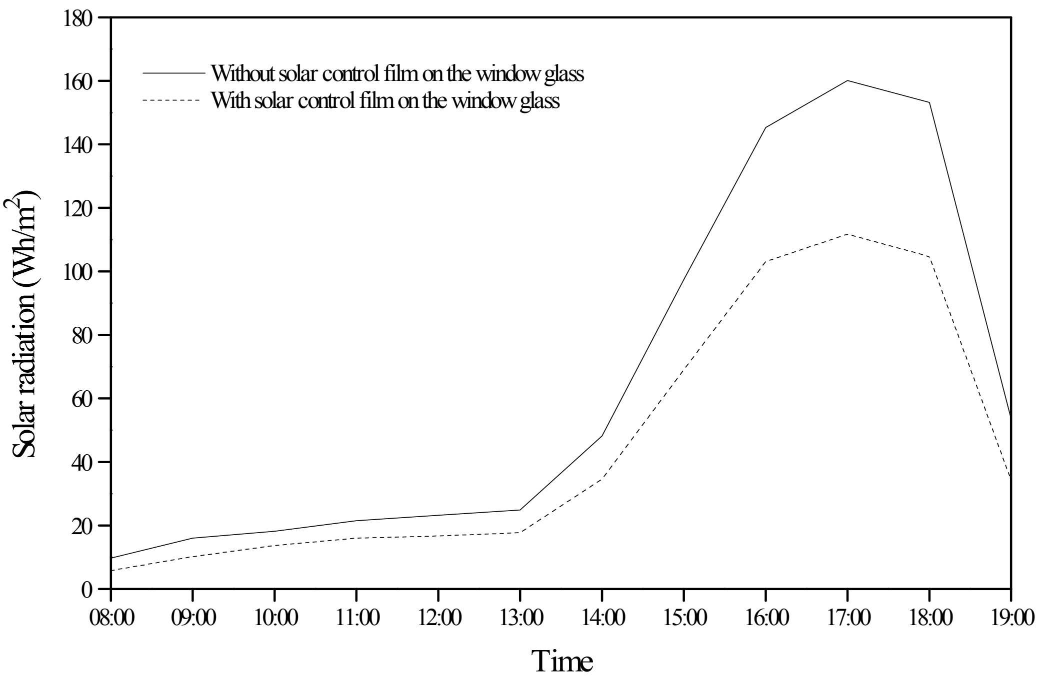


Figure 7.1 Measured daily solar radiation profile for the two offices

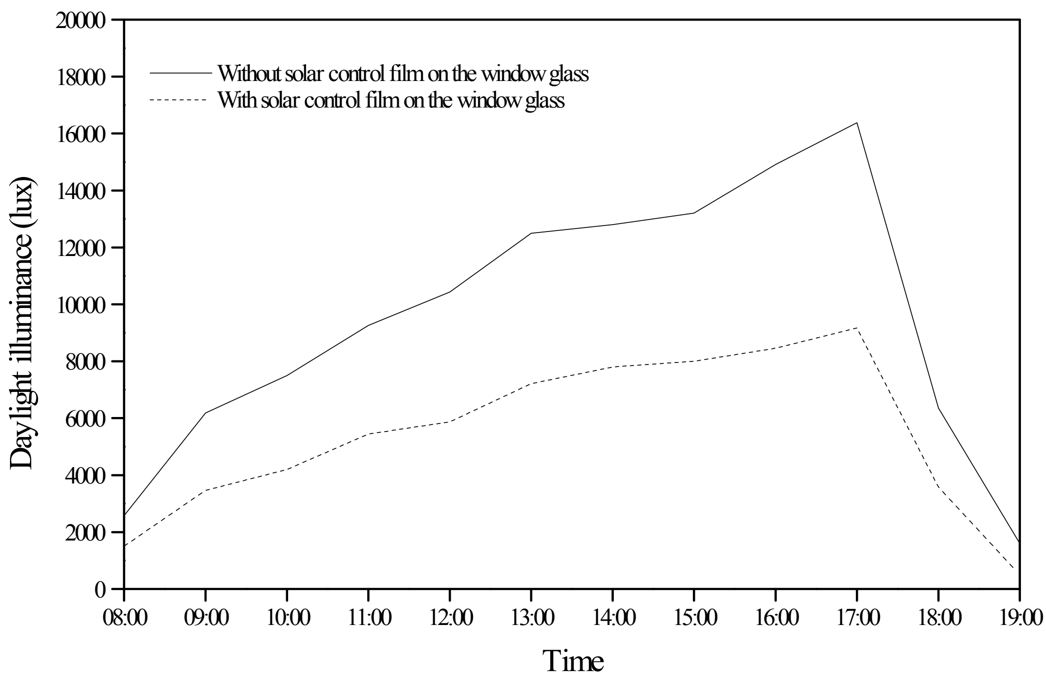


Figure 7.2 Measured daily daylight illuminance profile for the two offices

7.2.2 Daylight Availability

Figure 7.3 presents the frequency of occurrence of the transmitted daylight availability at an interval of 50 lux for an office with solar films on the windows. The daylight availability of the room without installation of solar control films is described in Section 4.2.3. To have a better presentation, the frequency of occurrence for data less than 50 lux accounting for about 3% is not shown in the figure. When the windows were covered by solar control films (i.e. between September 2004 and August 2005), the distribution of frequency of occurrence is skewed to the left with a peak also showing up at 5,000 lux. The maximum transmitted daylight illuminance of less than 28,000 lux is observed from the figure. The cumulative frequency distribution of daylight availability for the office space was determined and two curves representing the transmitted daylight for the uncoated windows and windows coated with solar control films are shown in Figure 7.4. The effects due to the film coatings can be observed from the two curves. For a small daylight illuminance which usually corresponds to overcast days for both cases, the percentage difference between the two curves is small. For high daylight levels, the discrepancies can be very significant. For instance, at an illuminance of 5,500 lux, the difference between the cumulative frequency distribution of the windows with and without coatings can be up to 30%. It shows that there would be a considerable difference in electric lighting energy savings for window glass with and without solar control film coatings when daylight-linked lighting controls are used.

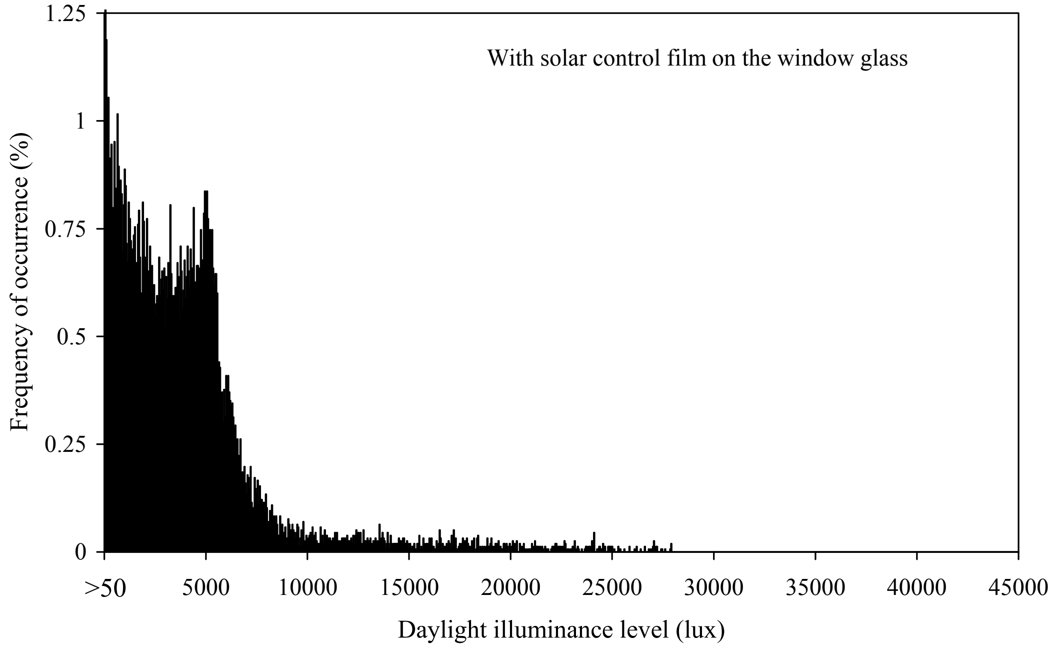


Figure 7.3 Frequency of occurrence for daylight availability

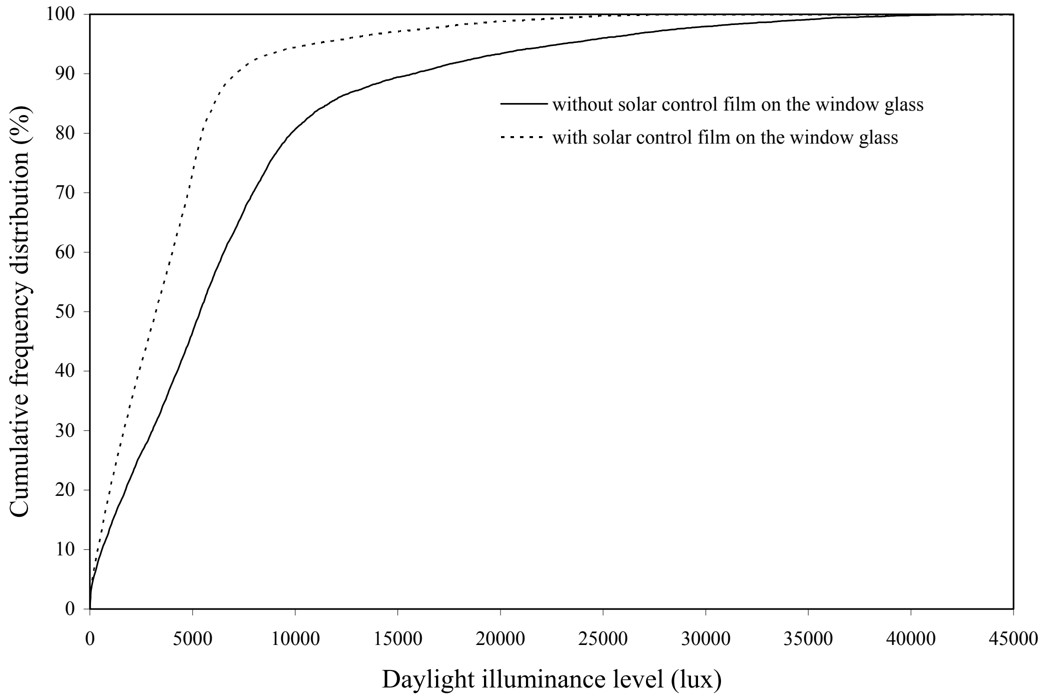


Figure 7.4 Cumulative frequency distributions for daylight availability

7.2.3 Electric Lighting Energy Consumption

Electric lighting energy consumption for the six fluorescent luminaries (two rows) in the office monitored by the automatic dimming controls with a 500 lux set-point were recorded and analysed. In Chapter 4, Figure 4.2 presents the average daily lighting energy profile recorded from February to August 2004 when the solar control film was not yet used. Similarly, the average daily electric lighting load profiles from September 2004 to August 2005 are shown in Figure 7.5. With solar film coatings, the amount of daylight penetrating into the office was reduced, causing more amounts of electric lighting energy use and shifting the time for the lowest lighting load to around noon. The lamp fittings were slightly dimmed in the morning when the daylight illuminance falling onto the windows was purely diffuse. In general, the hourly lighting energy consumption was 0.1kWh or more than those presented in Figure 4.2. The smallest hourly value of 0.23kWh occurred at 13:00 in November. It is interesting to note that the electric lighting consumption at 16:00 in July was quite low. A close examination of the results indicates that the lamps were dimmed to the minimum light output for a number of hours in this period.

The areas under the lighting load curves represent the total amount of daily electric lighting energy used. Based on the logged electric lighting energy consumption data during nighttime, the electric lighting load (i.e. lamp fittings plus the dimmable electronic ballasts) for the two rows without the daylight-linked lighting controls was estimated to be around 430W. Taking a typical daily dimming system operating time of 10 hours (08:00 – 18:00), the daytime daily lighting energy expenditure was 4.3kWh for the two rows of light fittings. Compared with the electric lighting load in Figures 4.2 and 7.5, the amount of average daily energy

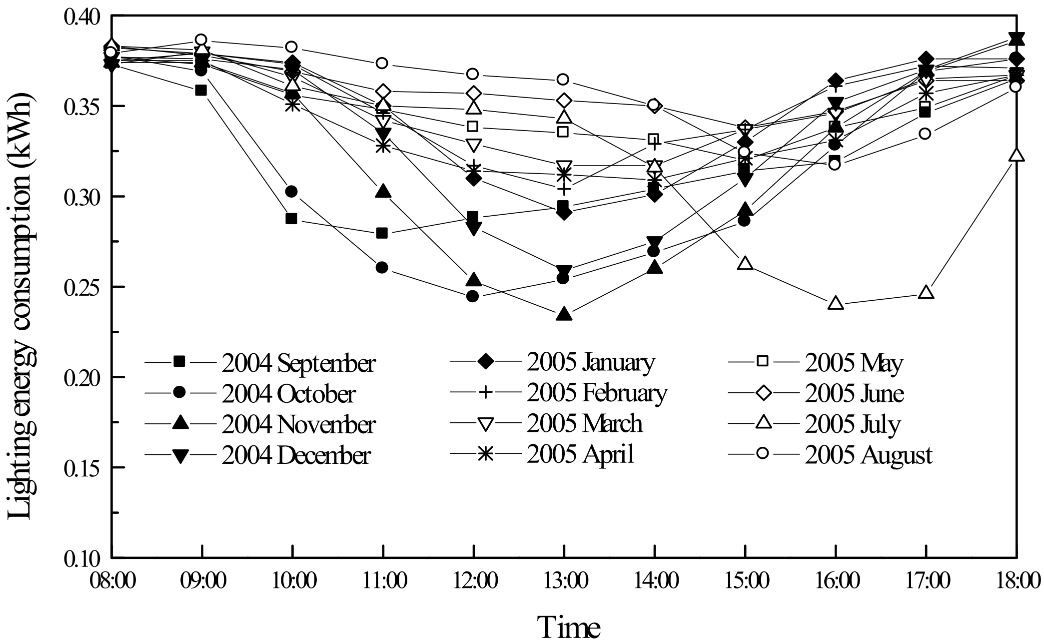


Figure 7.5 The average daily lighting energy profile recorded between September 2004 and August 2005

savings due to the high frequency dimming controls were obtained and are summarized in Table 7.1. The daily lighting energy reduction ranged from 0.72kWh in June 2005 to 1.67 kWh in June 2004. These denote 16.8 and 38.7% of the daily artificial lighting consumption. The average savings were 1.39kWh for the first 6½ months (without solar film coating) and 0.95kWh for the rest of the 12 months (with solar film coating). These represent reductions of 32% and 22% for the two rows of artificial lighting. The results were based on the existing dimming control system, which monitored only the two rows of luminaries near the window façade. With less amount of daylight contributing to the inner region, the percentage of electric lighting saving would be lowered if the dimming system was applied to the whole open-plan office. As mentioned, the lamps cannot be fully dimmed to extinction and consume certain residual energy. Such controls limit the electric lighting savings.

TABLE 7.1 Daily electric lighting energy savings

		Energy savings (kWh)											
Year	Status	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	Without solar control film	—	1.33 (31%)	1.09 (25.5%)	1.24 (28.7%)	1.46 (33.9%)	1.67 (38.7%)	1.57 (36.6%)	1.35 (31.5%)	—	—	—	—
2004	With solar control film	—	—	—	—	—	—	—	—	1.14 (26.6%)	1.24 (28.9)	1.14 (26.4%)	0.98 (22.8%)
2005	With solar control film	0.85 (19.7%)	0.81 (18.9%)	0.83 (19.4%)	0.94 (21.8%)	0.85 (19.7%)	0.72 (16.8%)	1.13 (26.3%)	0.74 (17.3%)	—	—	—	—

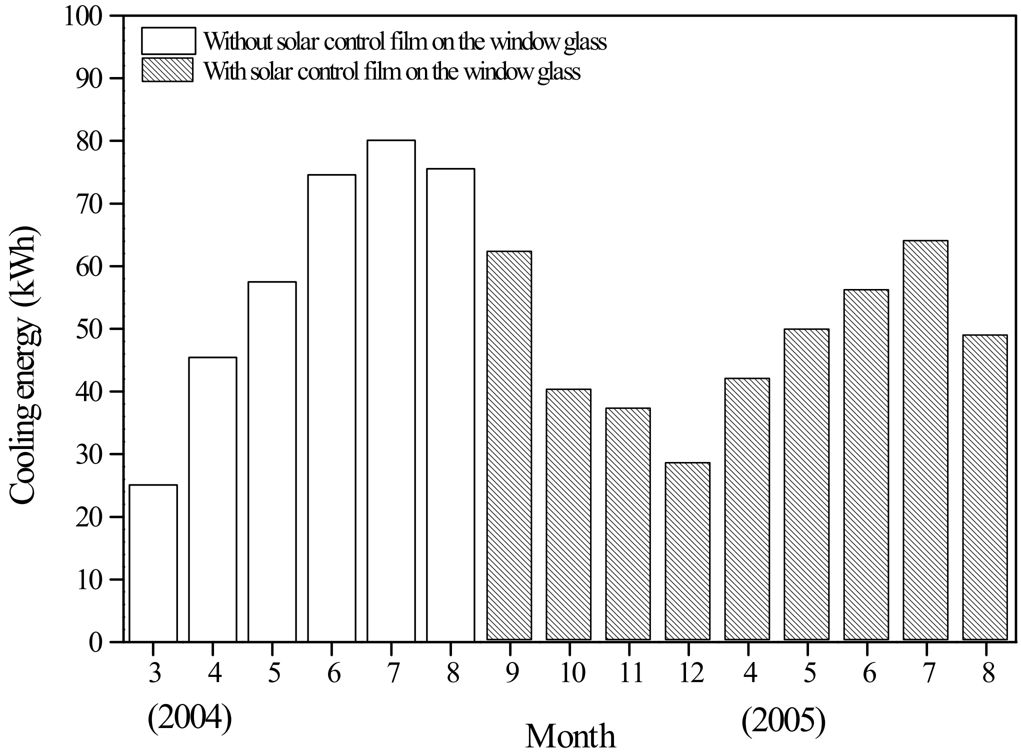


Figure 7.6 Daily cooling energy requirements in different months

7.2.4 Cooling Requirement

The chilled water flow rate and temperatures for the open-plan office were computed and studied. Figure 7.6 shows the daily cooling requirements from March 2004 to December 2004 and from April 2005 to August 2005. When the solar film coatings were not yet installed (March 2004 to August 2004), the findings are discussed in Section 4.2.4. With the window glass covered by the solar control films, significant cooling energy reduction can be found. As expected, quite low cooling requirements of below 40kWh were measured in October, November and December. For other months, the cooling energy requirements were substantially smaller than those months when the solar film coatings were not yet used. The reduction was more than 26kWh for August. It is expected that solar control film can reduce solar heat and hence the cooling requirements more effectively in summer months than in winter months. In general, the solar control film coatings together with daylight linked lighting control system can reduce the total energy consumption in the open-plan office particularly the cooling energy.

7.2.5 Computer Simulation

To have a thorough investigation of the overall effects due to the daylight-linked lighting controls together with the solar film coatings, the building energy program EnergyPlus was again used to simulate the annual building energy performance for the open-plan office. It is essential to determine the solar and visible transmittance values of the windows coated with the solar control films for the computer simulations (Smith et al., 1998). It has been pointed out in the literature that the optical properties of coated glass is rather complex because the multiple reflections within the coating's very thin layers exhibit interference patterns (Furla, 1991). Our previous findings also indicated that solar heat rejection of the solar control film relied on the amount of direct solar radiation received and the solar transmittance for the direct component should be expressed in terms of the angle of incidence (θ). The solar transmittance for diffuse radiation and visible transmittance of the film coatings are quite constant regardless of the amounts of diffuse radiation and the daylight illuminance recorded (Li et al., 2004). It would be appropriate to find out the visible and solar transmittances according to empirical results. Again, the simultaneous measurements for solar radiation and daylight illuminance in the two office spaces were used for the solar and visible transmittance determinations.

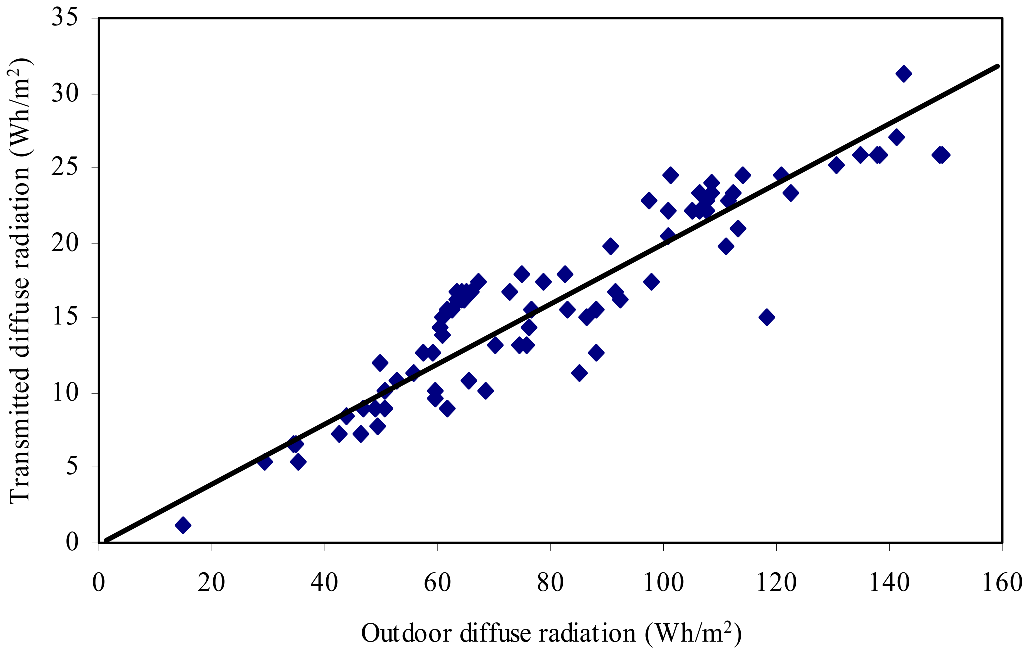


Figure 7.7 Correlation between outdoor diffuse radiation and diffuse radiation transmitted via the coated glazing

Using the optical properties and the information from the catalogue, the solar and visible transmittance values of the uncoated windows with respect to the diffuse component were estimated to be 0.295 and 0.635, respectively (Furla, 1991). Based on the data measured in the morning (i.e. purely diffuse component) the solar radiation falling onto the glazing (i.e. outdoor) were calculated and Figure 7.7 plots the outdoor diffuse radiation vs. the corresponding transmitted radiation measured in the office with the film coatings on the window glass. A linear trend between the indoor and outdoor diffuse components is evident from the graph. Likewise, the same approach was employed to determine the visible transmittance for the windows coated with the solar control films and similar features as in Figure 7.7 were found. Through regression analysis, the solar and visible transmittances of the glazing coated with solar control films were computed to be 0.2 with R^2=0.83 and 0.3664 with R^2= 0.995, respectively. Fresnel's equations were used again to predict the

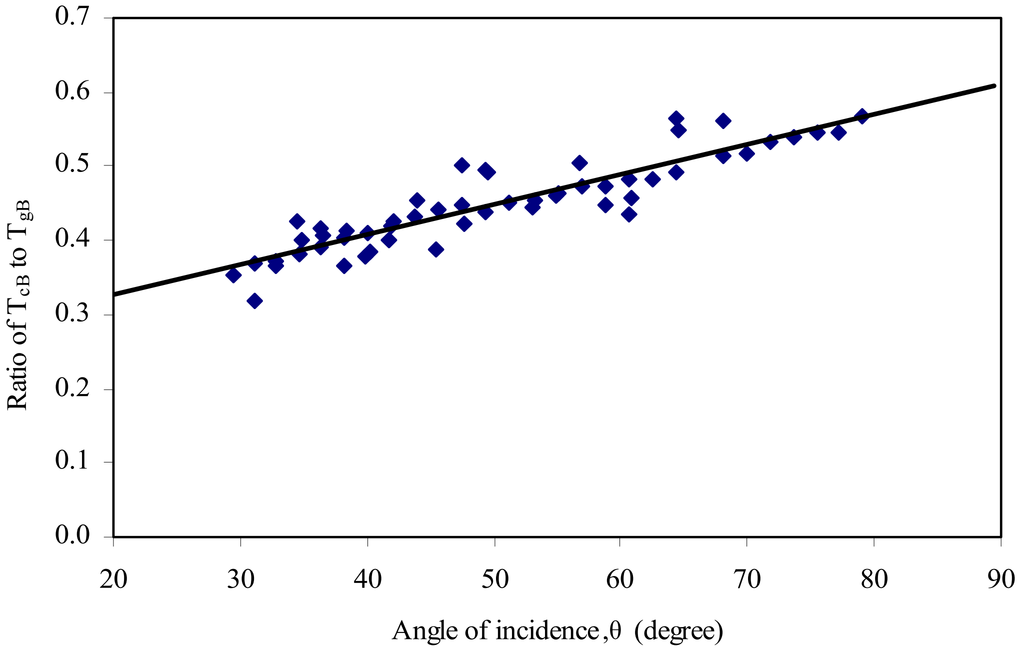


Figure 7.8 Correlation between θ and the ratio of T_{cB} to T_{gB}

angular solar transmittance (T_{gB}) and the visible transmittance due to the direct component of the uncoated window. Using the measured data in the two offices and the direct beam radiation measured in our measuring station (Furla, 1991), the angular solar transmittances of the coated windows (T_{cB}) at various θ were obtained. To have a better predictive ability, the ratio of T_{cB} to T_{gB} was plotted against θ and Figure 7.8 exhibits the results. A linear regression analysis was carried out and the mathematical expression is given as follows:

$$\frac{T_{cB}}{T_{gB}} = 0.0041\theta + 0.2447 \tag{7.1}$$

With R^2 of 0.821, the correlation is considered strong and T_{cB} can be determined based on various θ and T_{gB}. For simplicity, the visible transmittance for direct beam illuminance via coated glazing was computed based on the correlation between the outdoor direct beam illuminance and the corresponding transmitted daylight illuminance measured in the office with the film coatings on the window glass. Figure 7.9 shows such a correlation. Through regression analysis, the visible transmittance was estimated to be 0.3707 with R^2=0.949.

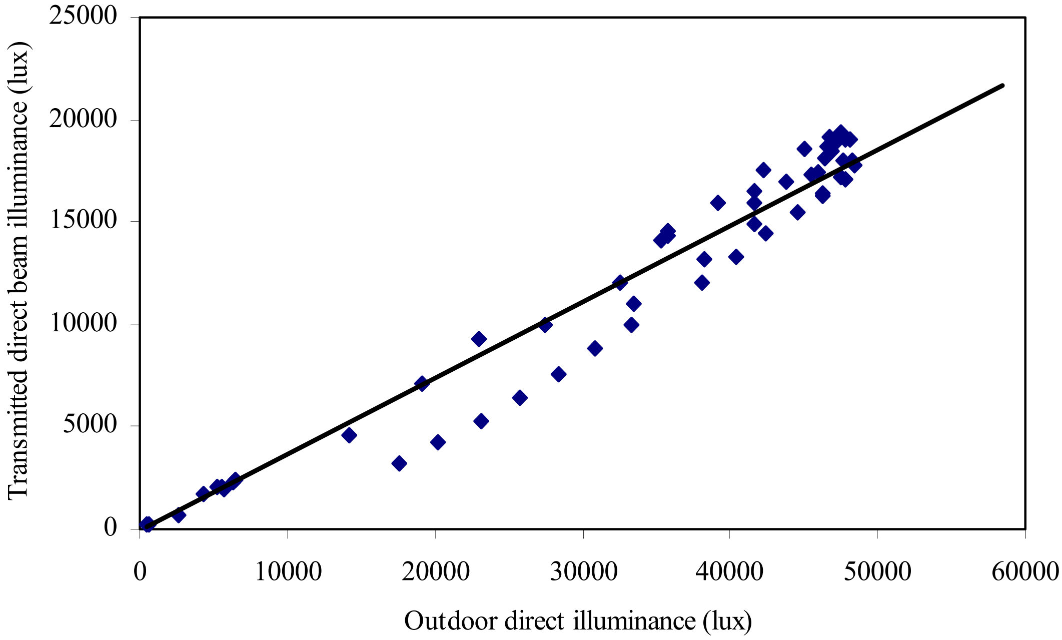
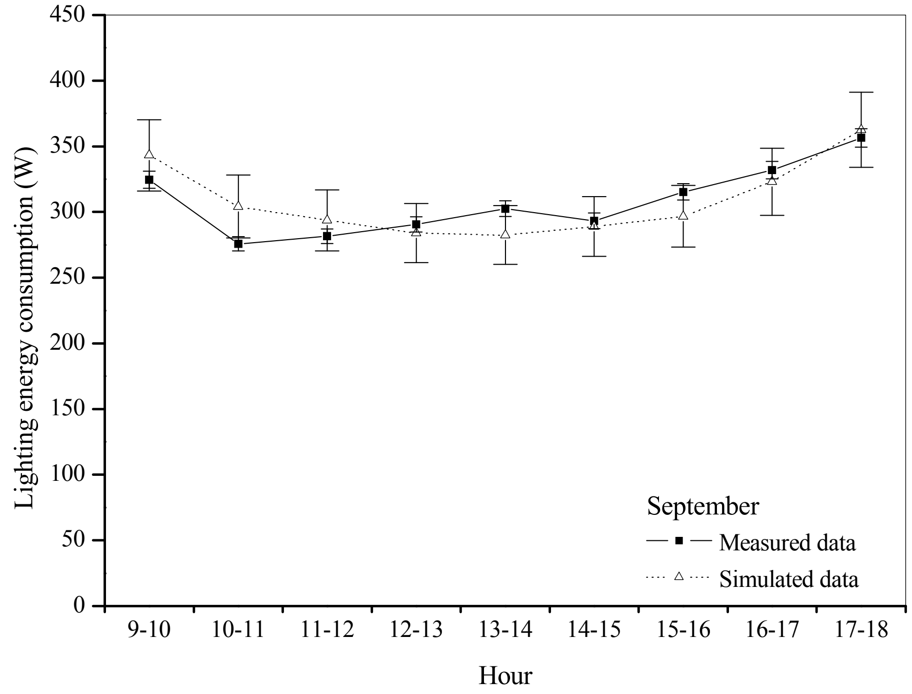


Figure 7.9 Correlation between outdoor direct beam illuminance and direct beam illuminance transmitted via the coated glazing

Accordingly, the characteristics of the solar control films including the solar and visible transmittances of the coated and uncoated windows (the modifications for the window calculation algorithm of the EnergyPlus program can be found in Appendix II), the building materials, equipment schedules and the weather data during the measurements were input into EnergyPlus for the building energy simulations. The horizontal global and diffuse components of solar radiation for the simulation runs were obtained from our measuring station (Li et al., 2002b). A summary of the key parameters is already given in Table 4.1 of Chapter 4. Moreover, the plots of field-measured and computer-simulated lighting energy consumptions for March to August (windows without solar control films) are already illustrated in Figures 4.8 and 4.9 of Chapter 4, respectively. To validate the applicability and accuracy of the above formed four optical equations used in building energy predictions, Figure 7.10 presents the plots of field-measured and computer-simulated lighting energy consumptions for September to December (windows with solar control films). It can be observed that the simulated data are reasonably close to the measured values. In some cases, the predicted and measured values almost overlap. A detailed examination of the figure reveals that the lighting energy expenditure is simulated more accurately in March to August than that in September to December. It can be seen that the application of optical equations of the solar film coating increase uncertainties in the simulations. Likewise, the simulated and measured cooling requirements were analyzed. The simulated and measured cooling requirements in September to December were computed and are displayed in Figure 7.11. The equipment accuracy for measuring lighting consumption and cooling requirement were ±2% and ±1.5%, respectively. The uncertainties associated with the optical properties of the glazing and room factors such as internal reflection and external obstructions caused the errors for lighting energy prediction (Loutzenhiser et al., 2007). The uncertainties including indoor air set-point temperatures, supply air temperature and flow rate were accounted for by cooling energy error analysis. The error bar represents the overall uncertainties between the simulated and measured results. It can be observed that most of the results were reasonably predicted using simulation techniques. The peak differences of 389kWh for October are observed. These represent about 9.4% of the corresponding measured values. Similar performances were found for other months. To further examine the performance of the program, MBE and RMSE were employed. Table 7.2 summarizes the MBE and


Lighting energy consumption (W)
450
400
350
300
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200
150
100
50
0
9-10
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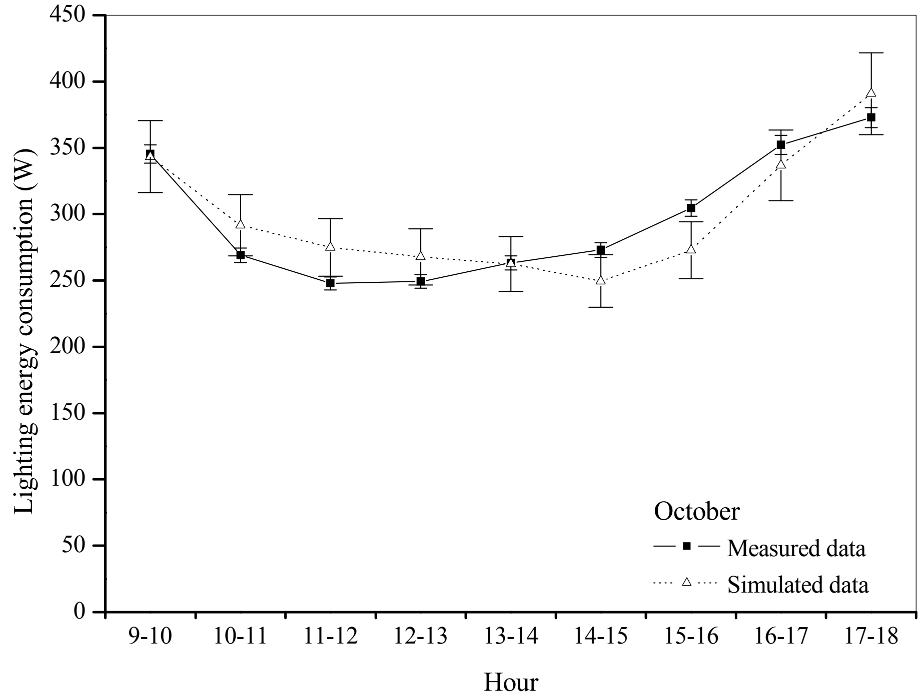
Hour
September
Measured data
Simulated data


Lighting energy consumption (W)
450
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Hour
October
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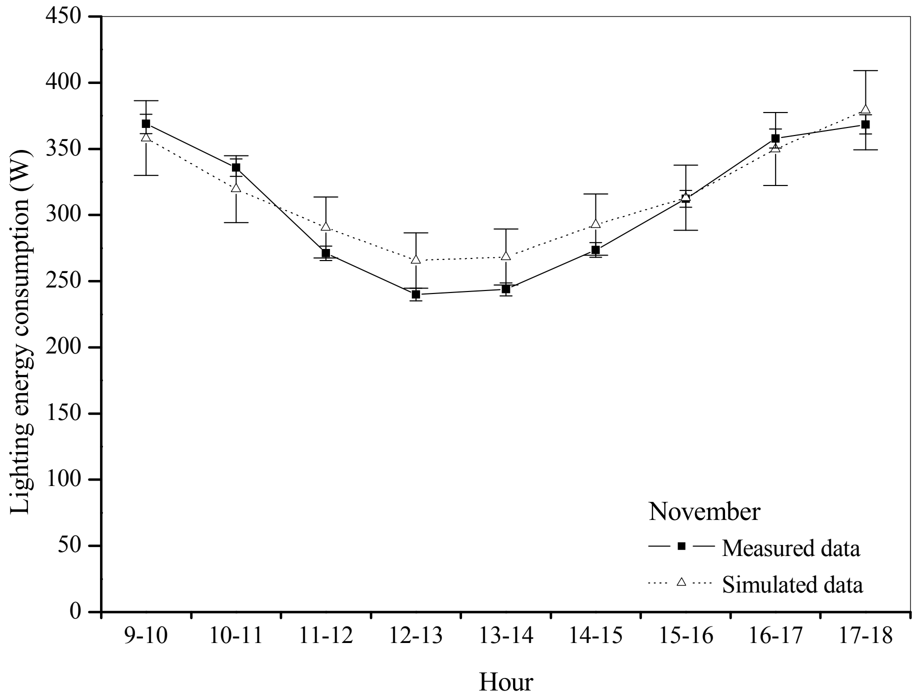


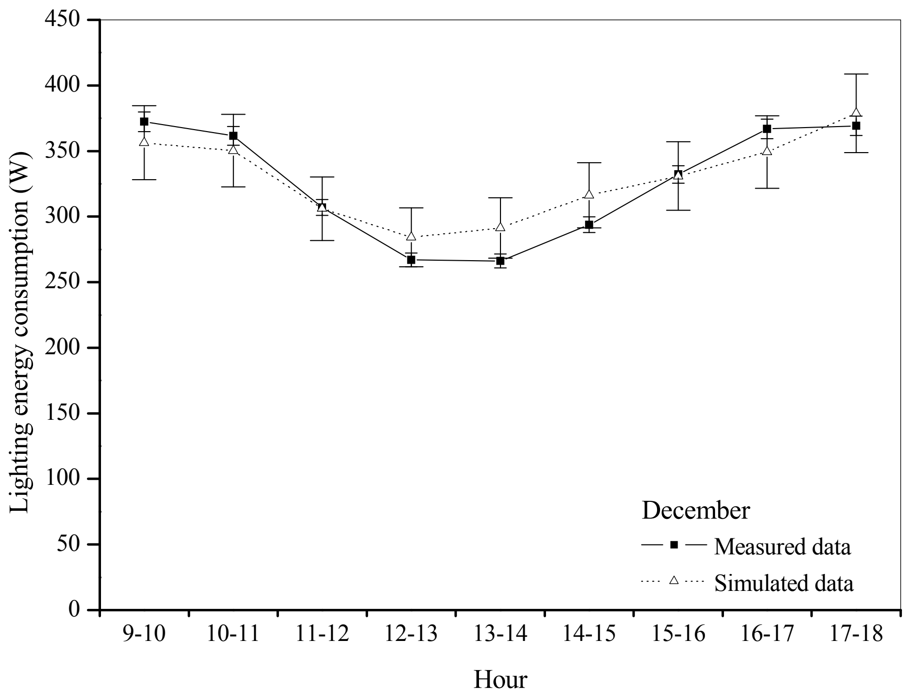
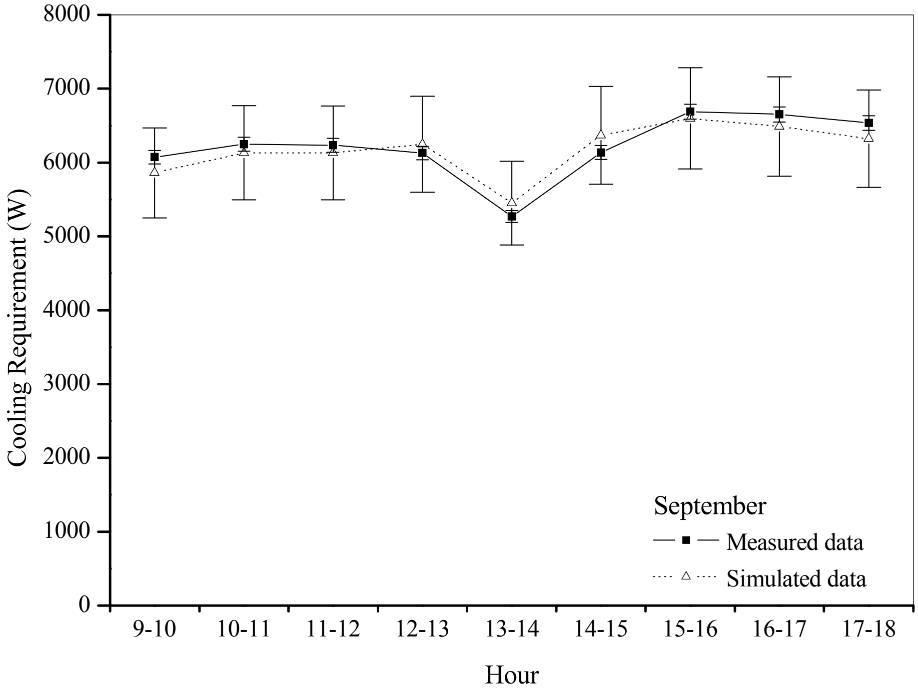


Figure 7.10 The field-measured and computer-simulated lighting energy consumption for September to December (windows with solar control films)


8000
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Cooling Requirement (W)
9-10
10-11
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16-17
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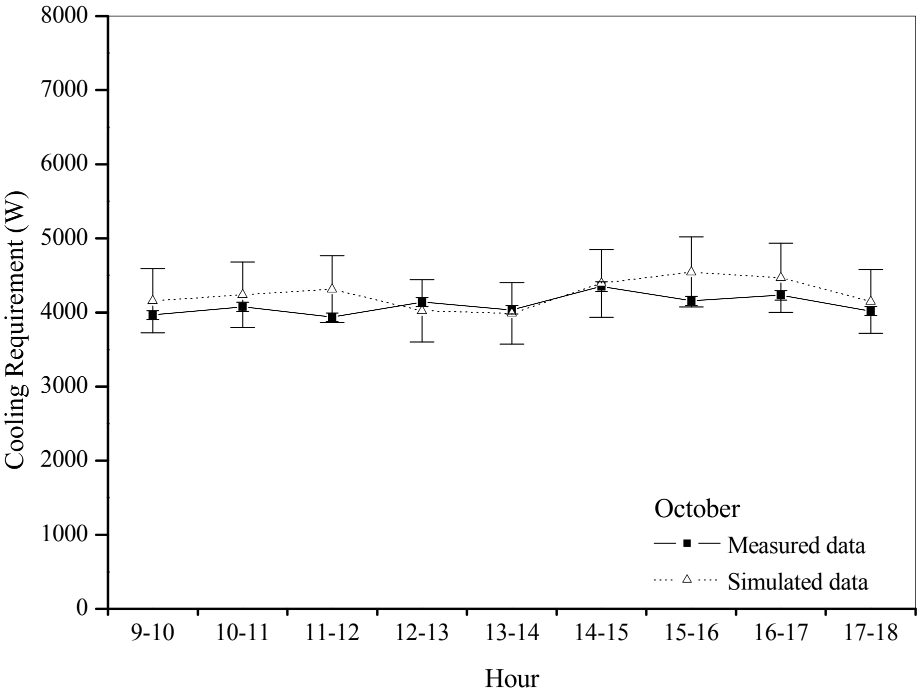
Hour
September
Measured data
Simulated data


8000
7000
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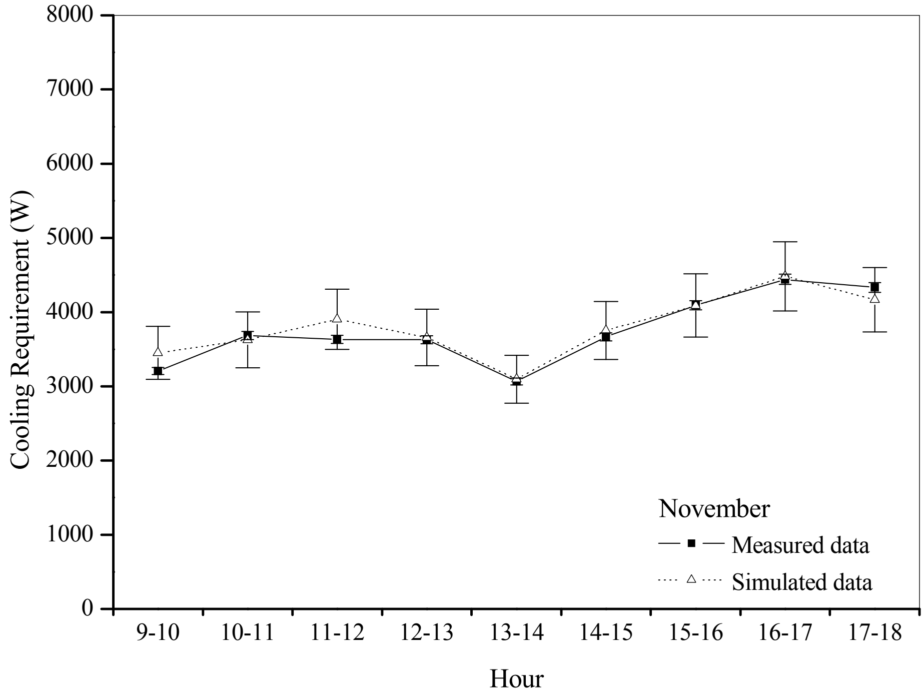
4000
3000
2000
1000
0
Cooling Requirement (W)
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
Hour
October
Measured data
Simulated data



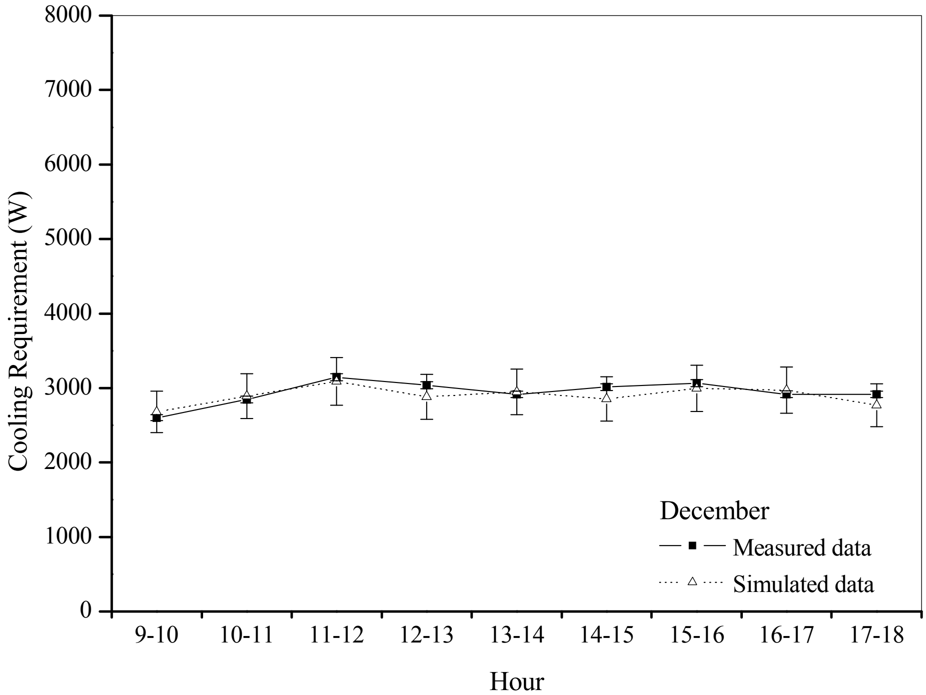


Figure 7.11 The field-measured and computer-simulated cooling energy consumption for September to December (windows with solar control films)

TABLE 7.2 Summary of MBE and RMSE for simulated lighting energy use and cooling requirement for September to December (windows with solar control films)

		with solar control film			
		Sep	Oct	Nov	Dec
Lighting	MBE (%)	0.2	0.5	2.4	0.9
	RMSE (%)	5.1	6.8	5.5	4.8
Cooling	MBE (%)	-0.7	3.7	1.4	-1.4
	RMSE (%)	2.7	5.5	3.7	3.4

RMSE for the lighting and cooling electricity expenditure in different months. For lighting energy consumption, the MBE values range from an overestimation of 0.2% in September to 2.4% in November. The largest RMSE is 6.8% appearing in October. Referring to the electricity cooling requirements, the MBE and RMSE vary from -1.4% to 3.7% and from 2.7% to 5.5%, respectively. The statistical results indicate that the building energy use can be simulated with a reasonable accuracy even using the self-derived optical equations for the solar control film.

The annual energy expenditure due to lighting and cooling requirements for the open-plan office using solar film coatings together with high frequency dimming controls was further simulated based on the same settings. Figure 7.12 illustrates the results using the weather data during the experimental analysis (i.e. 2004-2005). With the daylight-linked dimming control, the annual lighting energy for the two rows of the light fittings dropped from 1,139kWh to 785kWh, representing a 31.1% reduction. As less sensible heat gains were generated by artificial light fittings, the annual cooling energy consumption lowered from 4,477kWh to 4,299kWh, accounting for only a 4% drop. When the solar film coatings were installed together with the dimming controls, the lighting energy of 897kWh and cooling energy requirement of 4,169kWh were simulated. The findings represent 21.2% lighting energy and 6.9% cooling requirement savings. The small cooling energy saving may be due to the moderate direct solar radiation received by the office for the whole year. The simulated overall electricity savings for the open-plan office space are slightly lower than the case without using the solar control films. Therefore, the energy efficiency of buildings using solar control films should be further analysed.

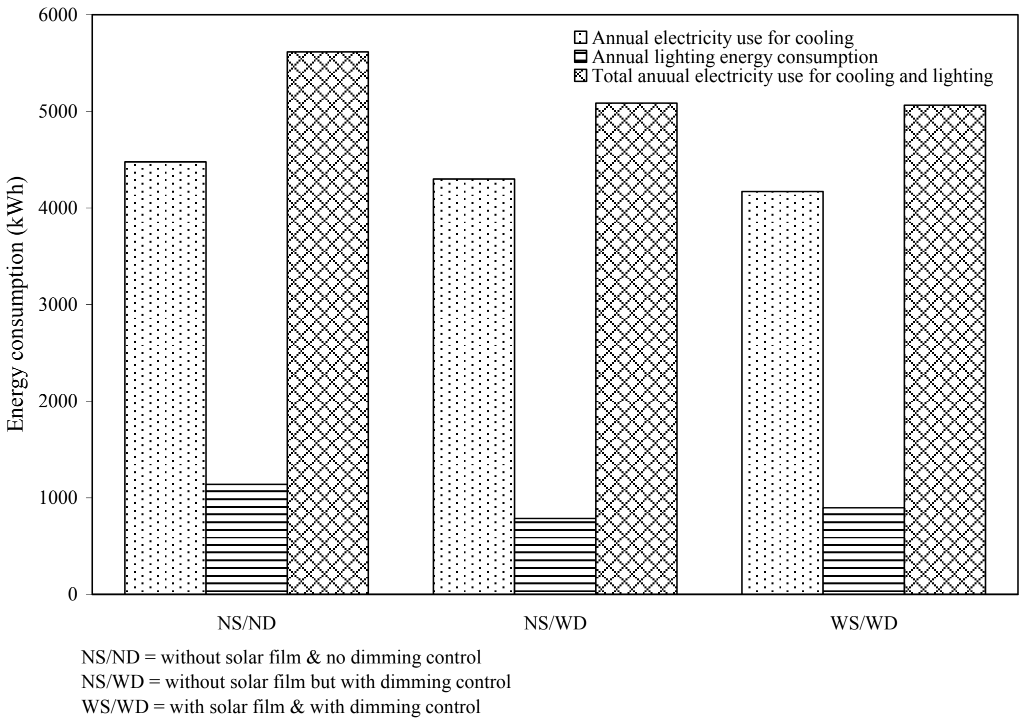
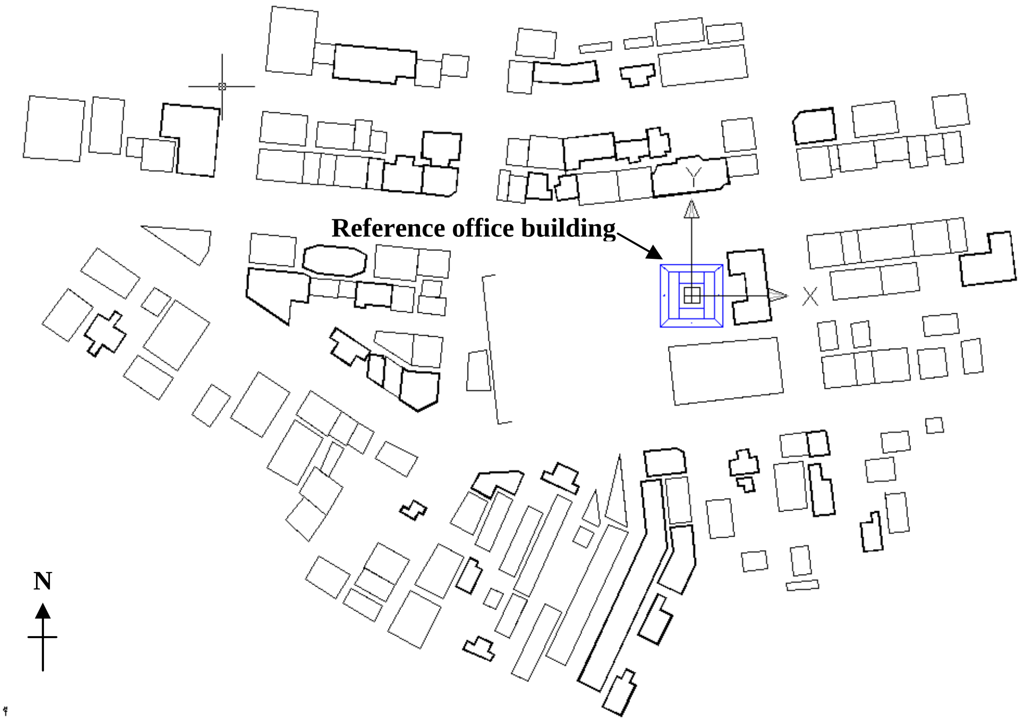


Figure 7.12 The computer-simulated annual lighting and cooling energy consumption for the open-plan office

7.3 Retrofit of Existing Buildings

The rate of replacement of old buildings with new buildings is very slow in Hong Kong. Thus effective building retrofits can certainly reduce energy use in the buildings. High-rise office buildings (20 storeys or higher) were built in Hong Kong during the 1980s. Most buildings constructed in that period tended to have larger windows with tinted glass (Lam et al., 2004). It resulted in high total building energy use, particularly for central air-conditioning systems. Methods for improving the quality and use of daylight in existing buildings are of great importance, both from the viewpoint of an improved work environment and for energy savings (Baker and Steemers, 2002). Moreover, installation of solar control coatings can also be considered since it applies to most clear or tinted glazing for lowering the solar penetration. The utilization of daylighting together with solar control coatings may be effective in improving energy performance for buildings.

Previous work (Li and Tsang, 2008) revealed that in Hong Kong the average WWR of 0.42 was estimated for buildings using tinted glass windows. Based on this, a generic existing office building was developed to serve as a baseline reference for comparison and evaluation. The reference building had a similar building configuration (i.e. building area, orientation, number of storeys, etc.) with the base-case office model developed in Chapter 3. Building envelope design of the reference building was reinforced concrete with inserted windows, which was different from the curtain wall design for the base-case model. Glazing was changed to single tinted glass (SC=0.65 and LT=0.5) with a WWR of 42% and the U-value of the spandrel wall was 1.91W/m^2°C. For daylighting simulation, the daylight control point of 500 lux was kept and top-up controls were also used for dimming the electric lighting installed at the four perimeter zones in response to the daylight available. The other building characteristics, i.e. lighting installation, HVAC system, operating schedules, etc., were not changed. To obtain reliable building energy expenditure, the base-case building was modelled in a real urban context, Wan Chai, in Hong Kong. This approach accounts for the shading effects due to nearby obstructions, which would reduce the direct beam solar radiation and contribute to the reflected component. A



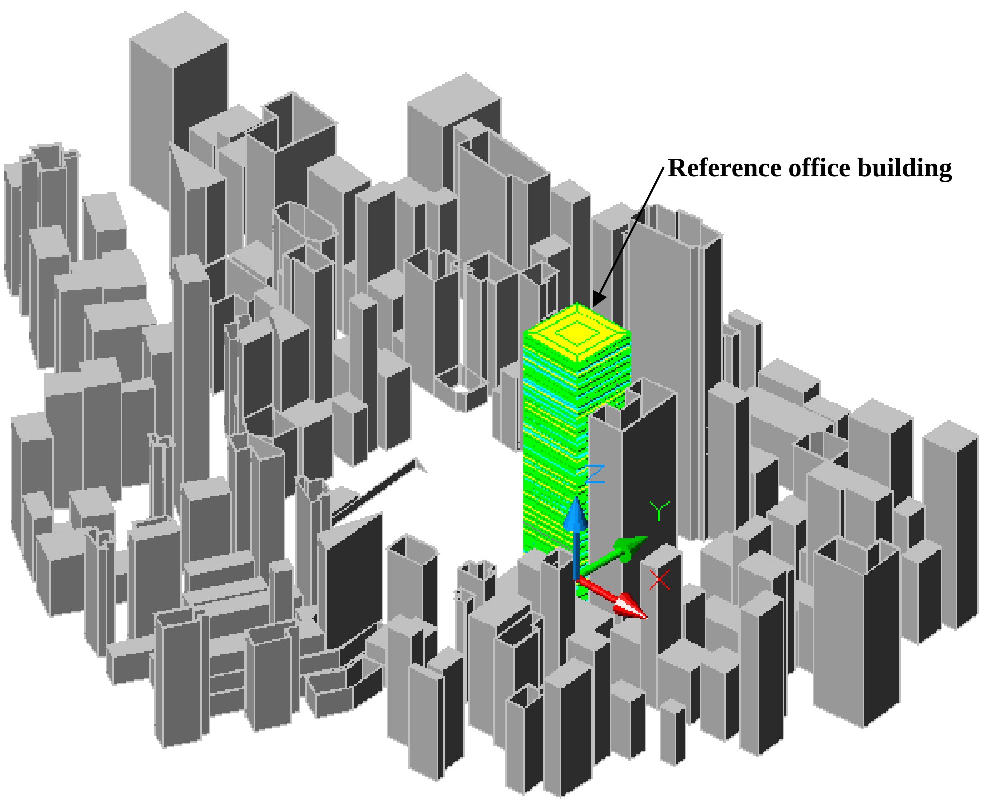


Figure 7.13 Plan and elevation views of the generic office building generated by EnergyPlus

reflectance of 0.2 for all façades of external buildings (Compagnon, 2004) was assumed. Figure 7.13 shows the exterior plan and elevation views for the simulation runs. The typical weather year in IWEC format was used to perform hour-by-hour calculations of energy performance.

7.3.1 Energy Performance

Analysis of the simulation results of the reference building is important to understand the components and building parameters of the model. Three cases namely, (1) the reference building without daylighting controls and without solar film coatings (w/o DC and w/o SFC), (2) with daylighting controls and without solar film coatings (w/ DC and w/o SFC), and (3) with daylighting controls and with solar film coatings (w/ DC and w/ SFC) were considered and analyzed. In this study, the solar control coating was attached on the west-facing vertical windows only, aiming to reduce the direct beam solar radiation entering into the building. The thermal and energy performances due to the solar control coatings were investigated in terms of total annual building electricity consumption, peak electricity use and the maximum cooling requirement.

Annual Electricity Consumption

The simulated annual electricity consumption is 10.4GWh for case 1 (w/o DC and w/o SFC). This represents an energy utilization index of 212kWh/m^2 which is slightly larger than the base-case model using reflective glass glazing. The annual building electricity consumption was broken down into six components, namely, electric lighting, office equipment, space cooling, fans, pumps and space

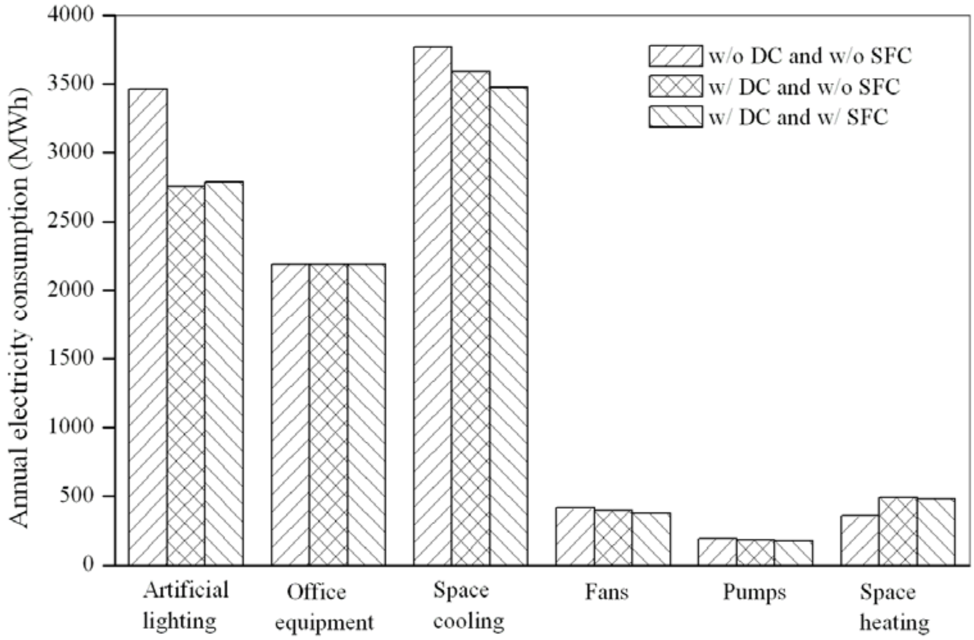


Figure 7.14 Breakdown of annual electricity consumption for a reference office building of tinted glass windows with different design options

heating. Figure 7.14 shows the breakdown of annual electricity consumption for final end-use. Cooling and heating systems are the most important components since they represent about 46% of total energy expenditure. The internal electric loads (lighting and equipment) account for the remaining 54%. The computed results show that air-conditioning and artificial lighting contribute over 75% of total building electricity consumption indicating the importance of lighting and solar heat gain in cooling-dominated commercial office buildings in subtropical climates. With daylighting controls (i.e. Case 2: w/ DC and w/o SFC), the annual electricity consumption is lowered to 9.60GWh. The EUI is 196kWh/m², representing a 7.6% reduction. The finding is smaller than the reference building facing unobstructed sky, showing that the shading effects can significantly lower the daylighting savings. By using Equation 6.11, the predicted energy reduction of the reference building due to daylighting controls is 14.5kWh/m^2, which underestimated the energy saving of 1.5kWh/m^2 when compared to the simulated results. It implies that the equation can reasonably predict energy saving potential of different daylighting schemes even in complex built environments.

The figure also shows that the annual lighting use for Case 2 is decreased by around 700kWh, which is about 20% of the total electric lighting use and corresponds to 7% of the total building's energy expenditure. The finding also gives a smaller but noticeable reduction of 4.85% in cooling energy resulting from less sensible heat gains generated by artificial light fittings. There is a slight increase in space heating, due mainly to a small drop in heat dissipation from electric lighting during the short heating season. When the solar film coatings coupled with lighting dimming controls are used (i.e. Case 3: W/ DC and W/ SFC), the lighting energy of 2,786kWh and cooling energy requirement of 4,027kWh were simulated. The results represent 19.6% light energy and 8% cooling requirement savings. Compared with Case 2, less cooling requirements but more electric lighting energy expenditure were consumed. The annual building energy use is reduced to less than 9.5GWh, accounting for an electricity reduction of 8.7%.

Peak Loads

The peak electricity loads occur at exactly the same time and date (26^{th} July at 5pm) for all three cases. To further analyze the electrical demands, peak building electricity expenditure was again broken down into the six components and is shown in Figure 7.15. For Case 1 (w/o DC and w/o SFC), the peak electricity load is 4,723kW. Air-conditioning energy requirements dominate the total energy consumption, contributing about 68% to peak total energy expenditure. The internal electric loads (lighting and equipment), which are non-weather-dependent, account for the remaining 32% of the total building energy use. When daylighting controls

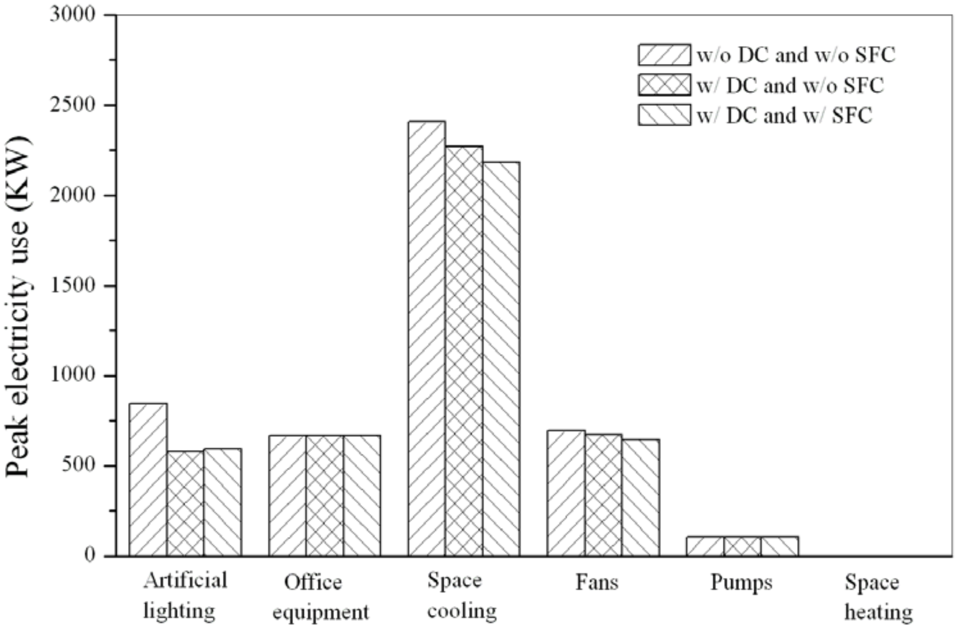


Figure 7.15 Breakdown of peak electrical demand for a reference office building of tinted glass windows with different design options

are in operation (Case 2: w/ DC and w/o SFC), the peak electricity use is lowered by 9% to 4,295kW. By using Equation 6.12 for calculating the E_{IPEUI}, the predicted peak energy use of the reference building due to daylighting controls is 4,223kW, which is around a 1.7% underestimate of the simulated result. Electric lighting load is substantially reduced by 267kW, which is about one-third of the electric lighting load and corresponds to 5.6% of total building electricity consumption. The electricity consumed by the HVAC system is decreased from 3,208 to 3,050kW, representing a 5% reduction. When the solar film coatings are used together with the dimming controls (Case 3: w/ DC and w/ SFC), the electricity use by the HVAC system and electric lighting load are 2,933 and 592kW, respectively. The peak total building electrical demand decreases further to 4,192kW accounting for an 11.1% drop compared with Case 1. The cooling plant capacity depends on the peak cooling load. The peak cooling requirements for Cases 1, 2 and 3 were simulated to be 6741, 6404 and 6112kW, respectively. The peak cooling demands for Cases 1 and 2 appear at exactly the same time and date as the peak electricity expenditure for the three cases (i.e. 26th July at 5pm). The peak cooling plant demand for Case 3 shifts to 4pm on 20th September indicating that large amounts of direct beam solar radiation is reduced by the solar film coatings in summer afternoons when the west-facing facades are normal to the sun. With a reduction of 9.3% in peak cooling demand, a smaller HVAC plant of lower capital cost can be selected for use.

7.3.2 Parametric Analysis

To facilitate an understanding of electricity benefits after retrofits (w/ DC and SFC), the window area is often changed parametrically in computer simulations. The window height was varied using six WWRs ranging from 0.3 (1.05m) to 0.6 (2.1m) at 0.1 increments including the WWR of 0.42 and WWR of 0.65, which is the maximum allowable window area for the façade on every floor. The minimum WWR of 0.3 was chosen for the buildings with tinted glazed windows (Li and Tsang, 2008). It should also be mentioned that too small window area may affect the view and connection with the outdoor environment, and may not comply with the local Building Regulations regarding minimum natural light and ventilation requirements (HKSAR, 1997). In contrast, a large fenestration area and tinted glass windows contribute to high solar heat gain and may not meet the OTTV requirement of 30W/m². Therefore, most of the buildings built in the 80s cannot comply with the OTTV requirement (Lam et al., 2004). However, daylighting is always an energy saver provided that the heating and cooling loads do not increase significantly. A higher OTTV can also result in less electricity consumption than the reference building envelope design if a proper daylighting control is adopted. The following parametric analysis can illustrate the likely savings.

Annual Electricity Consumption

The annual building electricity consumption of using daylighting controls and solar film coatings under the six WWRs were simulated and compared with the models without daylighting controls and solar film coatings and Figure 7.16 shows the results. The daylight and solar heat gain admitted through the building envelope offers an opportunity to significantly affect the lighting and cooling requirements. For the cases without considering the energy conservation schemes, large WWR means more solar radiation enters into the building and results in high cooling load for the building. Since internal loads such as electric lighting and office equipment remain the same for all design options, therefore, annual building energy consumption continuous to increase from 10.1GWh at WWR of 0.3 to 10.7GWh at WWR of 0.65. For buildings after retrofits, increasing window area will, on one hand contribute to more natural daylight and may significantly reduce electric lighting consumption. It, however, will only slightly increase the cooling demands due to admitting more solar radiation. With daylighting controls, the lighting requirements can be substantially reduced and, to a lesser extent, so can the cooling energy and heat rejection resulting from less sensible heat gains generated by artificial light fittings. At the same time, the solar film coatings can effectively reduce the solar heat gain inside the buildings. Therefore, there is slightly increased annual cooling energy from WWR of 0.3 to 0.65. It results a reduction trend of annual energy consumption when WWR is increasing. The annual building energy consumption is decreased from 9.6 to 9.5GWh ranging from WWR of 0.3 to 0.65.

Therefore, the total building energy expenditure is reduced from 565MWh at WWR of 0.3 to 1212MWh at WWR of 0.65, a range in energy saving of 5.6 to 11.4% after building retrofits.

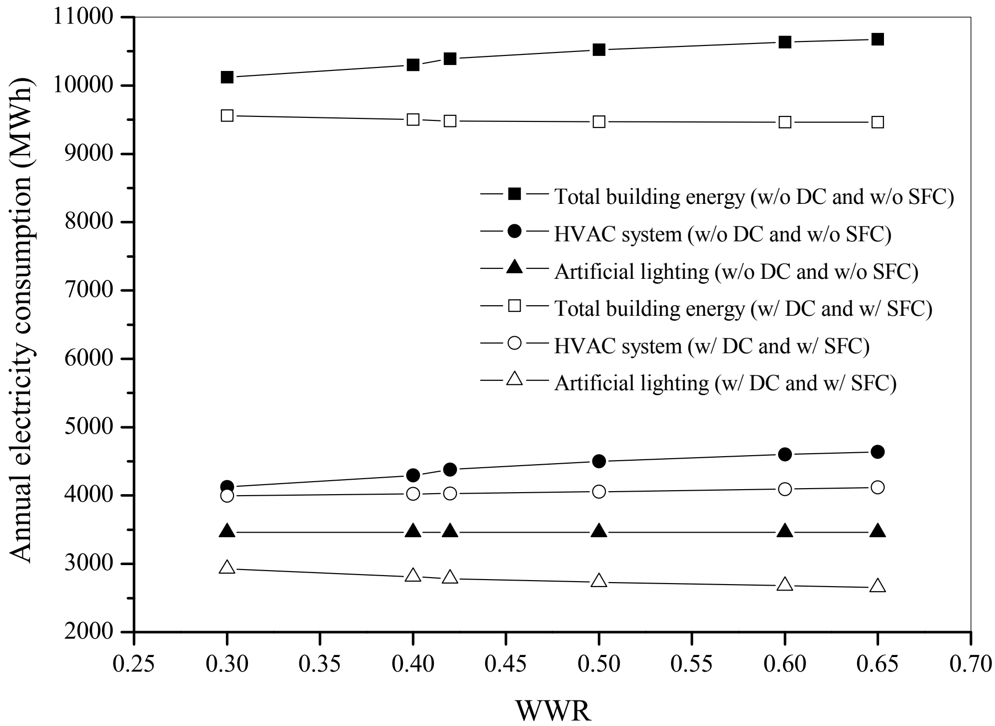


Figure 7.16 Comparison of annual electricity consumptions for a reference building with various WWRs before and after retrofits

Peak Electrical Demand and Cooling Requirement

The maximum electricity use of different WWRs with the energy conservation schemes was 4,398kW, which was smaller than that in the base-case model (w/o DC and w/o SFC) at WWR of 0.42. It reveals that solar control film together with daylighting controls can significantly reduce the peak loads for existing commercial buildings. The incremental peak electrical demands for various WWRs with daylighting controls and solar film coatings in operation are exhibited in Figure 7.17. The incremental peak electrical demands range from -186kW at WWR=0.1 to -681kW at WWR=0.65. The largest reduction in peak electrical demand appears when WWR=0.65 representing a reduction of 14% compared with the case without any improvements.

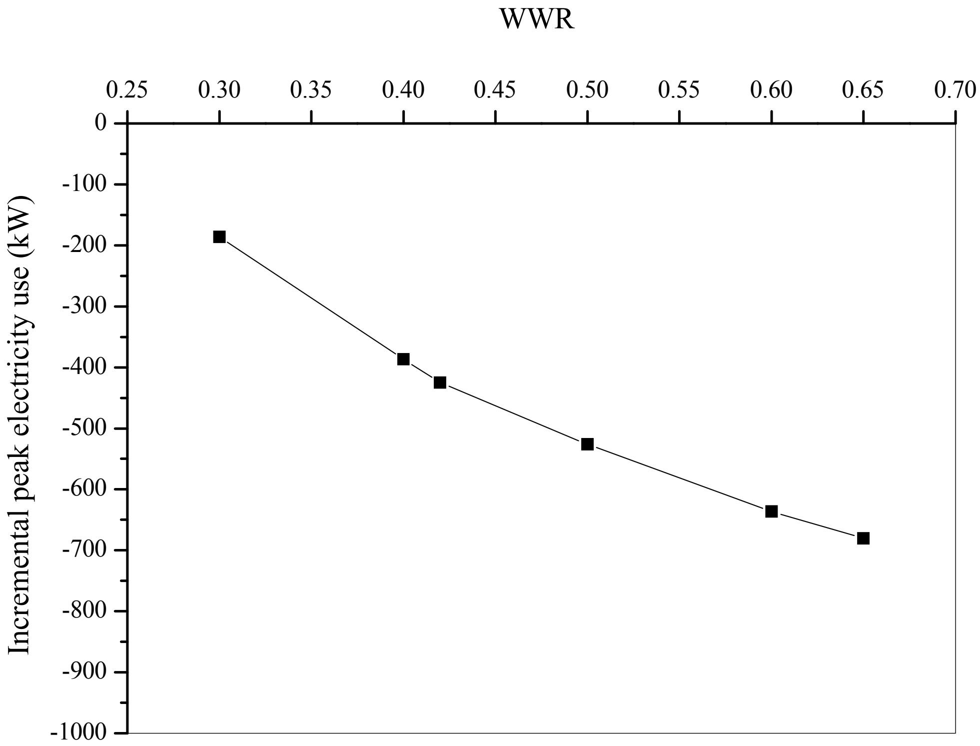


Figure 7.17 Incremental peak electricity use for a reference building with various WWRs

Likewise, the peak cooling demands under various cases were analysed and Figure 7.18 presents the findings. The decrease in cooling requirement is due mainly to less sensible load from lighting and solar film coating contributes an amount of cooling reduction. The pattern is quite different from the previous two figures (i.e. Figures 7.16 and 7.17). The peak cooling demand reduces gradually from WWR of 0.3 to 0.5. The trend is reversed after WWR of 0.5. The results show that more cooling requirements due to an increase in solar radiation are consumed and the reduction of sensible heat generated by artificial lighting reaches its maximum at WWR of after 0.5. The cooling plant requirement can be reduced around 9% for all WWRs. The highest peak cooling demand of 6,458kW still occurs at WWR of 0.65

and this value is only 47kW higher than that in the reference case (w/o DC and w/o SFC) at WWR of 0.3. The findings support the fact that in subtropical Hong Kong, a smaller cooling plant can be introduced if proper daylighting designs are applied to existing buildings undergoing major renovations.

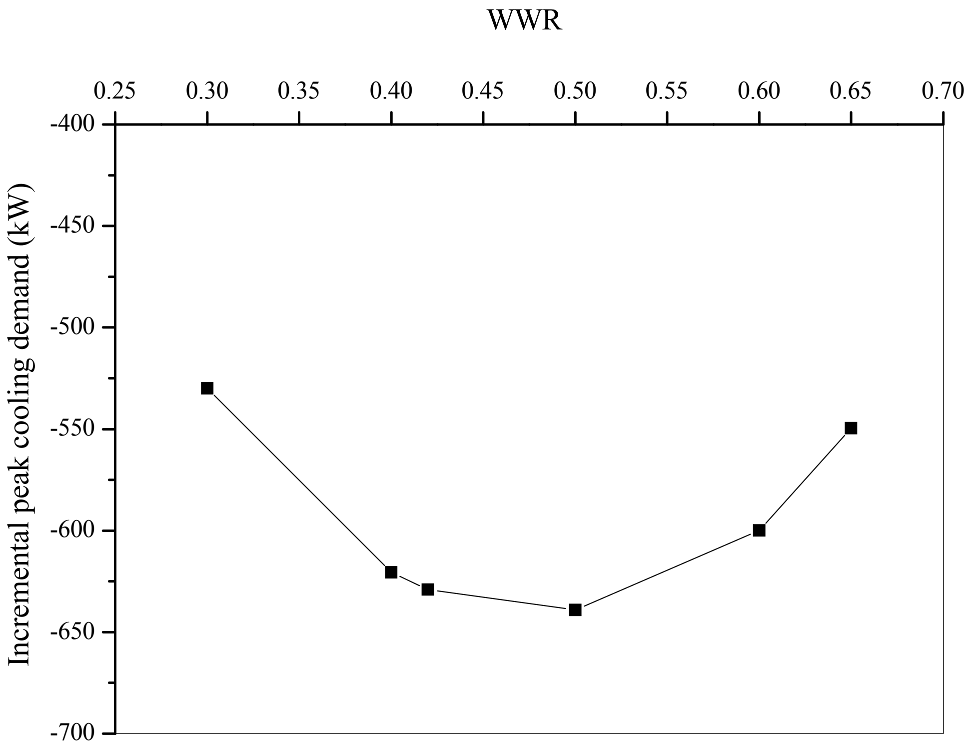


Figure 7.18 Incremental peak cooling requirement for a reference building with various WWRs

7.4 Summary

Field measurements of solar control film performance in an air-conditioned open-plan office with daylight-linked lighting controls were conducted. Important parameters including transmitted solar radiation and daylight illuminance, electric lighting and cooling energy expenditure for the office before and after the installation of the solar film on the windows glass were measured and presented. A solar film coating can substantially reduce the direct beam solar radiation and direct sunlight, contributing to energy-efficient building designs. With solar control films, the measured daylight illuminance levels, electric lighting savings and cooling energy consumption were considerably reduced. The remarkable cooling energy reductions occurred in the summer months only. The lighting and cooling energy expenditure was also simulated by the computer program EnergyPlus. The solar and visible transmittances of the glazing coated with solar control films were empirically determined according to the measured solar radiation and daylight illuminance data. It was found that the simulated results showed reasonably good agreement with the measured data. The study was extended to analyse the energy performance of whole building. To consider the shading effects due to nearby buildings, the external environments were modelled based on a business district in Hong Kong. When both dimming controls and solar control films were considered, 19.6% of the lighting energy and 8% of cooling energy savings were found. The reductions of peak electrical demand and peak cooling requirement were 11.1% and 9.3%, respectively. The substantial energy reductions were also found for different envelope designs of the building. The findings indicated that the solar film coatings coupled with lighting dimming controls could cut down considerably total building energy consumption, and peak electrical and cooling demands. It also implies that replacement cost of building services equipment can be lowered under building retrofits due to selection of smaller capacity of a cooling plant and electrical installations. Finally, it was revealed that the energy reductions due to different daylighting schemes can be reasonably predicted by using the equations of E_{IEUI} and E_{IPEUI} even in a complex external built environment.

Chapter 8 Conclusions and Recommendations

This thesis investigates three important aspects on daylighting and its energy impacts in air-conditioned high-rise buildings: (a) analysis of simulated and measured data, (b) building energy prediction models and (c) energy-efficient design for existing buildings. This chapter summarizes the major findings of the research work, states the limitations of the study and gives recommendations for future work.

8.1 Summary of Major Findings

Major findings of the research work for daylight availability and building energy reductions, development of building energy performance graphs and energy equations based on the simulation results, and the applicability of daylighting schemes for existing buildings are presented.

8.1.1 Daylight Availability and Energy Impacts

A computer simulation technique is introduced to evaluate daylighting and building energy performances in this study. Buildings' energy behaviour is highly influenced by indoor and outdoor circumstances. A base-case model was established for typical office buildings in Hong Kong. A set of outdoor design conditions for HVAC applications and a weather database for building energy and daylighting analysis were also established. Simulation outputs were also analysed and examined by the measured results.

Design Weather Data and Typical Weather Year

Based on the long-term weather databases (27 years), three outdoor design conditions namely, T_{clw}, T_{clg} and SCLF for building cooling load analysis were determined from the computer simulation results. The finding shows that the current design weather criteria will lead to overestimated cooling capacity of air-conditioning plants. It implies that there is potential to reduce cooling plant size and to achieve better building energy efficiency if accurate design data are used. Building designers should, therefore, consider the appropriate design weather data according to their applications and acceptable risk levels.

To perform long-term building energy estimations due to daylighting controls, the representative weather years for Hong Kong were determined based on the TMY and IWEC methods. It was found that the variations of the daily mean DBT of the format are closer to the long-term mean than the TMY. The variations of the DBT of the IWEC do not only perform well, but also the daily total GSR does. However, they give similar characteristics of outdoor global illuminance distribution. Daylighting alone can provide an office with 2% daylighting design for all sky conditions for over 60% of working hours. This indicates that daylighting schemes can be major energy-efficient design features. The two weather files were then employed in energy prediction tests together with the 27-year weather files. The monthly energy profile of the TMY and IWEC were found to have very similar patterns with the long-term predictions even for buildings with daylighting control. The smallest RMSE for IWEC weather dataset was found. It reveals that the IWEC weather database can represent prevailing climatic conditions to perform energy analysis in this study.

Measured vs Simulated Data

Measurement of daylight availability and indoor illuminance, electric lighting energy and cooling requirement for an open-plan office in Hong Kong was described and analysed using statistical and graphical methods. For well over 50% of the measuring period of 7 months, the recorded daylight illuminance readings were over 5,500 lux and the peak value was recorded at 43,000 lux. Since the office faces northwest, higher transmitted daylight illuminances would be expected for rooms facing in other orientations in Hong Kong. It was found that energy savings in electric lighting for the office was over 30% due to dimming control. To estimate the annual lighting and cooling energy reductions, the building energy simulation program, EnergyPlus, was employed. Computer models of the office design were built and the year 2004 was used for the simulation. With daylighting controls, the estimated energy savings for lighting and cooling were 30 and 4%, respectively. It is envisaged that a lower cooling load can be achieved due to the reduction of heat dissipation from artificial lighting. The exercise was also extended to validate the applicability of the simulation software for daylighting and energy analysis. Using a statistical approach, the building energy use can be simulated with reasonably accuracy using the measured data. It implies that the selected building energy simulation program and developed weather files are reliable for use in this study.

Importance of Building Design Parameters

Due to lack of flexibility in measurement of the office, study of the design parameters affecting daylighting and energy performance cannot be performed. The importance of each design parameter should be clearly defined for energy efficient building designs. The computer program was employed to test how the sensitivity and output results would be affected by the changes of building design parameters. The simulated results for the base-case model indicate that the annual electricity consumption can be reduced by 10% under daylighting control. The annual lighting energy and cooling energy requirements are decreased by 26 and 6%, respectively. Similar characteristics are also found in peak electricity analysis. Besides the total energy reduction, there is a potential to lower the building services installation cost, since smaller electrical and cooling plants are introduced. It is revealed that daylighting can be considered an energy conservation measure for new building development.

The sensitivity findings show that the most important design parameters are: window-to-wall ratio, light transmittance and height of external obstructions. It is found that total energy and peak electricity reductions have similar behaviour in sensitivity analysis. Single regression models have been established for building envelope design variables. The simple equations are useful to the building designers during the conceptual design stage when different single design parameters are being considered and assessed.

8.1.2 Building Energy Prediction Models

Daylighting designs and OTTV implications through a computer simulation technique have been discussed. Energy prediction models to determine annual electricity and peak load reductions with different envelope designs and daylighting schemes were established. Energy impacts of external obstructions on the whole building and individual floors were also analysed. Regression techniques which are often used for studying building energy performance and developing overall energy equations were also examined.

Daylighting and OTTV

The OTTV standard is mandatory in Hong Kong to control the thermal aspects of building envelope designs. However, no daylighting credits are given to the OTTV calculations. Building energy consumption varies with OTTV and DA. Energy prediction graphs were developed for whole building and four perimeter zones, which could indicate the incremental electricity use under the combined impacts of OTTV and DA. With daylighting controls, the reference building with OTTV up to 80W/m^2 consumed the same or less amount of energy as the base-case model. The effect of orientation on the magnitude and pattern of electricity use was noted. North and east perimeter zones consume less energy than south and west, since a low portion of solar heat gain is received in the morning for office operation. The findings show that there is a trade-off between the beneficial daylight and unwanted solar heat. To achieve optimum daylighting design for buildings, careful selection of sizes and materials of fenestration systems for different orientations is essential. The findings also showed that utilizing daylight control can reduce the cooling plant capacity and peak electricity demand.

External Obstructions

Not only building envelope designs, but also daylighting performance are influenced by external obstructions. A computer simulation technique was employed to investigate the energy performance for a reference building with daylighting controls shaded by nearby buildings. The total energy reduction of 25 to 28kWh/m^2 for the four perimeter zones was simulated when the reference building was heavily obstructed. For an individual floor, the electricity savings decreased from 40 to 28kWh/m^2 when the angle of obstruction varied between 25º and 30º. A number of correlation equations were developed to evaluate the energy saving potential due to the impact of external obstructions at different orientations.

Energy Index

To optimise an energy-efficient building design, all the crucial design variables should be considered at the same time. A general form of energy equation was proposed for this issue which includes variables from two design parameter groups (building envelope and shading effect). Energy models with 8 parameters were established using non-linear regression techniques. This method is good for helping to develop simplified equations for expressing energy targets. Such energy reduction index can give architects and building engineers some basic and concise insight into the design and energy interrelationships during the initial conceptual design stage when various design schemes and concepts are being considered and compared.

8.1.3 Energy Conservation Designs for Existing Buildings

Field measurements were conducted for an office using a photoelectric dimming system together with solar control films on windows. Transmitted solar radiation and daylight illuminance, electric lighting consumption and cooling energy requirement for the office were recorded and analysed. Solar and visible performance of the solar control film was empirically determined by comparing the measured results of an identical office which had not installed solar control films on windows. The results indicated that the solar control film can greatly reduce direct beam solar radiation, resulting in lower cooling load. However, electric lighting saving potential will also be reduced. This energy conservation measure (daylighting controls plus solar control film on windows) is suggested to be applied in existing buildings undergoing refurbishment. A reference building of tinted windows was modelled in a real urban context in Hong Kong. When the ECM was considered, around 9% of the total energy, 20% of the lighting energy and 8% of cooling load reductions were determined. The findings support the fact that proper daylighting schemes can considerably reduce the replacement cost and the operating cost of building services equipment in existing buildings.

Although the work presented is based on the Hong Kong situation, it is envisaged that the methodology and design considerations are relevant to other cooling-dominated commercial buildings in other regions with similar weather characteristics or urban contexts. It is hoped that this study would be of interest to energy researchers and building designers concerned about energy and environmental issues in this region.

8.2 Limitations of the Study

There are some deficiencies and limitations of this study. They are listed as follows:

(i) Cooling load measurement – cooling requirements were only recorded for the room with daylighting controls. No identical room was selected to carry out the measurement for the case of no daylighting control. Although the estimated results were obtained by computer software, the errors should be addressed.

(ii) Energy prediction for buildings – there is a lack of real energy consumption data for buildings with daylighting controls which makes validation and calibration of energy models difficult. Although some simulated results were compared with the measured data, they cannot represent sufficiently the prediction of real energy use for any other daylighting schemes.

(iii) One simulation program – the computer simulation package (EnergyPlus) employed was developed in the USA which may not reflect all simulation approaches. The daylight analysis has not been examined thoroughly for different locations or climates. This may affect the results significantly. There are many other daylighting simulation programs (i.e. ADELINE and RADIANCE) that can be used to validate the results of EnergyPlus.

(iv) One reference case – although this is based on the survey of existing buildings and contains many common design features, it only considers one building form (i.e. square) and one particular air-conditioning system (i.e.

centralised VAV system). Studying the daylighting performance on other building forms and HVAC systems are also important. However, it will result in an exhaustive list of computer runs.

(v) Outdoor global illuminance – the simulation program uses luminance efficacy models developed by Perez et al. to convert global irradiance to illuminance for daylighting analysis. Measured daylight data is regarded as the most accurate information to evaluate daylighting performance and simulate the thermal and energy performance of buildings.

(vi) Constant form of external obstructions – the nearby buildings were set out in a constant form including the separate distance from the base-case model and the width of the obstruction for shading effect analysis. The real urban context is rather more complex, particularly in Hong Kong. Therefore, the results are regarded as an indication of the likely magnitude.

(vii) Optical properties of solar control film – due to site constraints, the development of correlation equations was based on a few sets of measured data and the angle of solar incident was measured ranging from 30º to 80º only. The results only present a general overview of energy saving potential made by solar control film.

(viii) Application of solar control film – solar control film was only applied for west-facing windows; the findings may be only suitable for the particular site. These results may not totally reflect the actual performance of the coating, since building environment is different for each case.

8.3 Suggestions for Future Study

Future study and research development are recommended to enhance the work on prediction of daylighting and energy performance for high-rise buildings and the implications for energy efficient building design. The recommendations are as follows:

(i) Weather data for simulation – Markou et al. (2007) have developed a new typical weather dataset for daylighting analysis. Comprehensive studies should be carried out to find out the typical or representative weather dataset by comparing actual weather data and energy simulations. A long-term (30-year) weather database containing daylight data (measured and predicted results) and outdoor illuminance (global and diffuse horizontal illuminance) should be included as a critical parameter for typical year determination when daylighting is considered.

(ii) Analyses for other types of building – the approach and methodology in the study can be applied to other building types of different lighting levels and fittings that are implemented in building energy codes such as institutions, hotels, shopping centres, etc. and results can be compared to determine an effective daylighting assessment and strategy.

(iii) Analyses for different locations – the approach and methodology in the study can be applied to other locations with similar climates. Considering the rapid building development in southern China, this could have important energy use and environmental implications in this region.

(iv) Analyses using different simulation programs – some other simulation programs also integrated with daylighting facilities may give a more accurate result in other aspects (some would be better in daylight analysis and the others would be better in energy calculation). These packages should be studied so that the strength of each tool can be used to produce more representative simulation results.

(v) Survey on daylight quality – to promote daylighting design for buildings, visual comfort (mainly glare index) should also be measured and analysed in Hong Kong. It changes human behaviour through the use of internal shadings that can totally affect the energy expenditure of buildings with dimming control systems.

(vi) Part-load performance of cooling plant – daylighting can reduce the cooling capacity of air-conditioning systems in buildings. Part-load operations of chillers dominate cooling energy expenditure. Proper selection of an appropriate size of chiller and development of operating strategies for chillers according to outdoor dry-bulb temperature, solar radiation and illuminance can definitely cut down energy use in buildings.

(vii) Incorporate innovative daylighting designs into buildings – daylighting schemes have a great potential in building energy savings. Innovative daylighting technologies such as light pipes and laser cut panels have been well developed and their performance has been examined in other countries. However, their application is rare in Hong Kong. Studies should be conducted to integrate these technologies into building designs.

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Appendix I – EnergyPlus Input File for Base-case Office Building Using Daylighting Controls

Due to extensive length of the input files, therefore, some of the files have not been included in this section.

```
##fileprefix C:\Lee2\Lee\Basecase_imf\

!- -------------------General Information-------------------------

##include gen_info.idf
##include design_conditions.idf

!------------------Model----------------------------------------------

##include multipler.idf
##include externalzone.idf
##include internalzone_GF.idf
##include internalzone_typical.idf
##include internalzone_RF.idf
##include core_typical.idf
##include core_GF.idf
##include core_RF.idf

!-----------------Zone Load---------------------------------------

##include activities_sch.idf
##include zone_sch.idf
##include zone_sch_type.idf
##include infiltration.idf
##include zoneload.idf
##include zoneload_return.idf
##include zoneloads.idf
##include zone_autosizing.idf

!--------------------Material Construction------------------------

##include construction_material.idf
##include glazing_material.idf

!--------------------Active Facade Control----------------------

##include blindcontrol.idf
##include daylightdetail.idf

!------------------System----------------------------------------------

##include system_autosizing.idf
##include zone_temp.idf
##include supply_temp_sch.idf
##include VAV_heating.idf
##include setpoint.idf
##include system_avaliability_manager.idf

!--------------------Chiller Plant-------------------------------------

##include chilled_water_temp.idf
##include pump.idf
##include chillerplant.idf
```

```
##include plant_autosizing.idf
##include plantloop.idf
##include branch.idf
##include chillerCOP.idf

!-------------------------------------------------------------------------------

!-------------General Building Description----------------------------
!--Building Height ---

##set1 EWALL-HL = "3.5"                                   !        External Wall High level (TOP)
##set1 EWALL-LL = "0"                                     !        External Wall Low level (LOW)
##set1 WIN-HL = "2.5"                                     !        Window Top level
##set1 WIN-LL = "1"                                       !        Window bottom level
##set1 IWALL-HL = "3.5"                                   !        Internal Partition Height
##set1 IWALL-LL = "0"                                     !        Internal Partition Low level
##set1 CWALL-HL = "3.5"                                   !        Core Wall Height
##set1 CWALL-LL = "0"                                     !        Core Wall Low Level
##set1 ceilheight = "3.5"                   !             Ceiling Height

!--Building Construction--
##set1 ext_wall_type = "WALL-1"                           !        External wall construction
##set1 int_wall_type = "INT-PART"           !             Internal Wall Construction
##set1 window_glazing_type = "RE-GLASS with no shade"     !        External Wall Glazing Construction
##set1 floor_const_type = "FLOOR"          !             Typical Floor Floor Construction
##set1 ceiling_const_type = "CEILING"                     !        Typical Floor Ceiling Construction
##set1 ground_const_type = "GND-FLR"                      !        Ground Floor Construction
##set1 roof_const_type = "RF"                             !        Roof Construction
##set1 core_wall_type = "COREWALL"                        !        Core Wall Construction
##set1 core_ceiling_type = "CORECEIL"                     !        Core Zone Typical Floor Ceiling Construction
##set1 core_floor_type = "COREFLOOR"                      !        Core Zone Typical Floor Floor Construction
##set1 core_roof_type = "CORERF"           !             Core Zone Roof Construction

!--Shading Control--
!          Create a set of blind
##set1 shading_name = "Control on incident solar and glare"     !        Name of shading control
##set1 shading_construcion = "RE-GLASS with interior shade"     !        Name of shading construction
##set1 solar_setpoint_value = "200"        !             Setpoint value for shading on if above this solar irradiance
{W/m2}
##set1 Shading_glare_control = "Yes"       !             Any Glare control
window_shading_control[]                                  !        Create shading

!-------------Ground Floor Script------------------------------------

!          Parameter Zone
##set1 zonename = "GFSP_N"
##set1 azi_ang = "0"
##set1 IWALL1-outsidefaceenv = "GFSP_E:IWALL-3"
##set1 IWALL2-outsidefaceenv = "GFSP_I:IWALL-1"
##set1 IWALL3-outsidefaceenv = "GFSP_W:IWALL-1"
##set1 shading_control = "Control on incident solar and glare"     !        Shading control of window, leave it blank if
none
zone_GF[]                                                                   !        Create zone

##set1 zonename = "GFSP_E"
##set1 azi_ang = "90"
##set1 IWALL1-outsidefaceenv = "GFSP_S:IWALL-3"
##set1 IWALL2-outsidefaceenv = "GFSP_I:IWALL-2"
##set1 IWALL3-outsidefaceenv = "GFSP_N:IWALL-1"
##set1 shading_control = "Control on incident solar and glare"     !        Shading control of window, leave it blank if
none
zone_GF[]                                                                   !        Create zone

##set1 zonename = "GFSP_S"
##set1 azi_ang = "180"
##set1 IWALL1-outsidefaceenv = "GFSP_W:IWALL-3"
##set1 IWALL2-outsidefaceenv = "GFSP_I:IWALL-3"
##set1 IWALL3-outsidefaceenv = "GFSP_E:IWALL-1"
##set1 shading_control = "Control on incident solar and glare"     !        Shading control of window, leave it blank if
none
zone_GF[]                                                                   !        Create zone

##set1 zonename = "GFSP_W"
##set1 azi_ang = "270"
##set1 IWALL1-outsidefaceenv = "GFSP_N:IWALL-3"
```

```
##set1 IWALL2-outsidefaceenv = "GFSP_I:IWALL-4"
##set1 IWALL3-outsidefaceenv = "GFSP_S:IWALL-1"
##set1 shading_control = "Control on incident solar and glare"     !        Shading control of window, leave it blank if
none
zone_GF[]                                                                   !        Create zone

!        Internal Zone
zone_I_GF[]                                                                 !        Create Ground Floor
Internal Zone

!        Core Zone
core_GF[]                                                                   !        Create Ground Floor
Core Zone

!--------------------20/F Description-----------------------------------

!        Zone Multiplier and height
##set1 multipliers ="38"                                            !        Zone multipier for Typical Floor
##set1 typicalfloor-z-origin = "70"                                 !        Floor Height

!        Parameter Zone
##set1 zonename = "20SP_N"
##set1 azi_ang = "0"
##set1 IWALL1-outsidefaceenv = "20SP_E:IWALL-3"
##set1 IWALL2-outsidefaceenv = "20SP_I:IWALL-1"
##set1 IWALL3-outsidefaceenv = "20SP_W:IWALL-1"
##set1 shading_control = "Control on incident solar and glare"     !        Shading control of window, leave it blank if
none
zone_20[]                                                                   !        Create zone

##set1 zonename = "20SP_E"
##set1 azi_ang = "90"
##set1 IWALL1-outsidefaceenv = "20SP_S:IWALL-3"
##set1 IWALL2-outsidefaceenv = "20SP_I:IWALL-2"
##set1 IWALL3-outsidefaceenv = "20SP_N:IWALL-1"
##set1 shading_control = "Control on incident solar and glare"     !        Shading control of window, leave it blank if
none
zone_20[]                                                                   !        Create zone

##set1 zonename = "20SP_S"
##set1 azi_ang = "180"
##set1 IWALL1-outsidefaceenv = "20SP_W:IWALL-3"
##set1 IWALL2-outsidefaceenv = "20SP_I:IWALL-3"
##set1 IWALL3-outsidefaceenv = "20SP_E:IWALL-1"
##set1 shading_control = "Control on incident solar and glare"     !        Shading control of window, leave it blank if
none
zone_20[]                                                                   !        Create zone

##set1 zonename = "20SP_W"
##set1 azi_ang = "270"
##set1 IWALL1-outsidefaceenv = "20SP_N:IWALL-3"
##set1 IWALL2-outsidefaceenv = "20SP_I:IWALL-4"
##set1 IWALL3-outsidefaceenv = "20SP_S:IWALL-1"
##set1 shading_control = "Control on incident solar and glare"     !        Shading control of window, leave it blank if
none
zone_20[]                                                                   !        Create zone

!        Internal Zone for Typical Floor
##set1 zonename_I = "20SP_I"
##set1 IIWALL1-outsidefaceenv = "20SP_N:IWALL-2"
##set1 IIWALL2-outsidefaceenv = "20SP_E:IWALL-2"
##set1 IIWALL3-outsidefaceenv = "20SP_S:IWALL-2"
##set1 IIWALL4-outsidefaceenv = "20SP_W:IWALL-2"
##set1 ICWALL1-outsidefaceenv = "20CORE:CWALL-1"
##set1 ICWALL2-outsidefaceenv = "20CORE:CWALL-2"
##set1 ICWALL3-outsidefaceenv = "20CORE:CWALL-3"
##set1 ICWALL4-outsidefaceenv = "20CORE:CWALL-4"
zone_I[]                                                                    !        Create Typical Floor
Internal Zone

!        Core Zone for Typical Floor
##set1 zonename_C = "20CORE"
##set1 CCWALL1-outsidefaceenv = "20SP_I:CWALL-1"
##set1 CCWALL2-outsidefaceenv = "20SP_I:CWALL-2"
##set1 CCWALL3-outsidefaceenv = "20SP_I:CWALL-3"
```

##set1 CCWALL4-outsidefaceenv = "20SP_I:CWALL-4"
core[] ! Create Typical Floor Core Zone

!------------------------------Roof Floor Script------------------------------
! Parameters for Roof Floor
##set1 RF-z-origin = "136.5"

! Parameter Zone
##set1 zonename = "RFSP_N"
##set1 azi_ang = "0"
##set1 IWALL1-outsidefaceenv = "RFSP_E:IWALL-3"
##set1 IWALL2-outsidefaceenv = "RFSP_I:IWALL-1"
##set1 IWALL3-outsidefaceenv = "RFSP_W:IWALL-1"
##set1 shading_control = "Control on incident solar and glare" ! Shading control of window, leave it blank if none
zone_RF[] ! Create zone

##set1 zonename = "RFSP_E"
##set1 azi_ang = "90"
##set1 IWALL1-outsidefaceenv = "RFSP_S:IWALL-3"
##set1 IWALL2-outsidefaceenv = "RFSP_I:IWALL-2"
##set1 IWALL3-outsidefaceenv = "RFSP_N:IWALL-1"
##set1 shading_control = "Control on incident solar and glare" ! Shading control of window, leave it blank if none
zone_RF[] ! Create zone

##set1 zonename = "RFSP_S"
##set1 azi_ang = "180"
##set1 IWALL1-outsidefaceenv = "RFSP_W:IWALL-3"
##set1 IWALL2-outsidefaceenv = "RFSP_I:IWALL-3"
##set1 IWALL3-outsidefaceenv = "RFSP_E:IWALL-1"
##set1 shading_control = "Control on incident solar and glare" ! Shading control of window, leave it blank if none
zone_RF[] ! Create zone

##set1 zonename = "RFSP_W"
##set1 azi_ang = "270"
##set1 IWALL1-outsidefaceenv = "RFSP_N:IWALL-3"
##set1 IWALL2-outsidefaceenv = "RFSP_I:IWALL-4"
##set1 IWALL3-outsidefaceenv = "RFSP_S:IWALL-1"
##set1 shading_control = "Control on incident solar and glare" ! Shading control of window, leave it blank if none
zone_RF[] ! Create zone

! Internal Zone
zone_I_RF[] ! Create Roof Floor Internal Zone

! Core Zone
core_RF[] ! Create Roof Floor Core Zone

!-------------------------------Internal Load---------------------------------

##set1 ltg_load_density = "20" ! Lighting load density for office (W/m2)
##set1 core_ltg_load_density ="10" ! Lighting load density for core (W/m2)
##set1 eqp_load_density = "18" ! Equipment load density for office (W/m2)
##set1 occup_density = "8" ! Occupancy Density (m2/psn)

floorzone_load[] ! Arrange zone load

!-------------------------------daylighting-----------------------------------

##set1 x-coord = "0" !- x-coordinate of first reference point {m}
##set1 y-coord = "15.25" !- y-coordinate of first reference point {m}
##set1 z-coord = "0.75" !- z-coordinate of first reference point {m}
##set1 refpt1ill = "500" !- Illuminance setpoint at first reference point
##set1 azi_ang = "0" !- azimuth angle of view direction relative to window for glare calculation {deg}
##set1 glare_index = "22" !- The maximum allowable discomfort glare (DGI)
##set1 min_power_input = "0.12" !- The minimum power consumed by lighting {fraction}
##set1 min_lgt_output = "0" !- The minimum light can be output {fraction}

##set1 zonename = "GFSP_N"

```
p_zone[]
##set1 zonename = "GFSP_E"
p_zone[]
##set1 zonename = "GFSP_S"
p_zone[]
##set1 zonename = "GFSP_W"
p_zone[]
##set1 zonename = "20SP_N"
p_zone[]
##set1 zonename = "20SP_E"
p_zone[]
##set1 zonename = "20SP_S"
p_zone[]
##set1 zonename = "20SP_W"
p_zone[]
##set1 zonename = "RFSP_N"
p_zone[]
##set1 zonename = "RFSP_E"
p_zone[]
##set1 zonename = "RFSP_S"
p_zone[]
##set1 zonename = "RFSP_W"
p_zone[]
! daylightdetail.idf

!--------------------------System design parameters--------------------------

##set1 cool_s_temp = "14"          !- Zone cooling design supply air temperature {C}
##set1 heat_s_temp = "50"          !- Zone heating design supply air temperature {C}
##set1 oa_flowrate = "0.008"        !- outside air flow per person {m3/s}
zonesize[]
! zone_autosizing.idf

!---------------------------General System Description-----------------------

!                 Setpoint Temperature
##set1 zonesumtp = "24"                  !             Summer zone indoor temperature {C}
##set1 zonesumsbtp = "37"                !             Summer Setback Temperature {C}
##set1 zonesumbf = "26"                  !             Summer Zone indoor Temperature an hour before office
hour {C}
##set1 zonewintp = "21"                  !             Winter zone indoor temperature {C}
##set1 zonewinsbtp = "10"                !             Winter Setback Temperature {C}

##set1 fan_eff = "0.65"                  !             Overall fan efficiency       {fraction}
##set1 fan_delta_press = "1000"          !             Total delta pressure for fan {Pa}
##set1 fan_motor_eff = "0.85"            !             Fan motor efficiency {fraction}

zonetempsch[]                                          !             Create schedule according to  sepoint schedule
define before

##set1 supplyairtemp = "14"              !             Supply air temperature {C}
supply_temp_sch[]

##set1 fansch = "SystemAvail-Sch"     !             Schedule name of System operate
fan_sch[]
! system_avaliability_manager.idf

##set1 supplytempsch = "Seasonal reset supply temperature Sch"
##set1 zonecontrolsch = "Zone Control type sch"
##set1 heatsetpt = "Heating Setpoints"
##set1 coolsetpt = "Cooling Setpoints"
##set1 Heating_Setpoint = "HeatingSetpoint"
##set1 Cooling_Setpoint = "CoolingSetpoints"
##set1 VAVSetpoint = "VAV setpoints"
setpoint_sch[]
! setpoint.idf

##set1 systemname = "GF"
##set1 zone1 = "GFSP_N"
##set1 zone2 = "GFSP_E"
##set1 zone3 = "GFSP_S"
##set1 zone4 = "GFSP_W"
##set1 zone5 = "GFSP_I"
##set1 maxairflowrate = "12"
##set1 minairflowrate = "3.6"
```

```
##set1 CHW_flowrate = "0.0069608"
##set1 maxOA = "12"
##set1 minOA = "1.0290"
##set1 zone1airflowrate = "1.7"
##set1 zone2airflowrate = "2.3"
##set1 zone3airflowrate = "1.7"
##set1 zone4airflowrate = "3"
##set1 zone5airflowrate = "3.3"
##set1 zone1reheatcoilcap = "7500"
##set1 zone2reheatcoilcap = "7300"
##set1 zone3reheatcoilcap = "6000"
##set1 zone4reheatcoilcap = "6500"
##set1 zone5reheatcoilcap = "4500"
!Fan Pressure drop, fan and motor efficiency are defined above
Vav_c_nh[]
! VAV_heating.idf

##set1 systemname = "20SP"
##set1 zone1 = "20SP_N"
##set1 zone2 = "20SP_E"
##set1 zone3 = "20SP_S"
##set1 zone4 = "20SP_W"
##set1 zone5 = "20SP_I"
##set1 maxairflowrate = "475"
##set1 minairflowrate = "142.5"
##set1 CHW_flowrate = "0.2613488"
##set1 maxOA = "475.0"
##set1 minOA = "39.102"
##set1 zone1airflowrate = "68.4"
##set1 zone2airflowrate = "91.2"
##set1 zone3airflowrate = "68.4"
##set1 zone4airflowrate = "117.8"
##set1 zone5airflowrate = "129.2"
##set1 zone1reheatcoilcap = "285000.0"
##set1 zone2reheatcoilcap = "269800.0"
##set1 zone3reheatcoilcap = "193800.0"
##set1 zone4reheatcoilcap = "228000.0"
##set1 zone5reheatcoilcap = "136800.0"
!Fan Pressure drop, fan and motor efficiency are defined above
Vav_c_nh[]
! VAV_heating.idf

##set1 systemname = "RF"
##set1 zone1 = "RFSP_N"
##set1 zone2 = "RFSP_E"
##set1 zone3 = "RFSP_S"
##set1 zone4 = "RFSP_W"
##set1 zone5 = "RFSP_I"
##set1 maxairflowrate = "13.5"
##set1 minairflowrate = "4.05"
##set1 CHW_flowrate = "0.0070431"
##set1 maxOA = "13.5"
##set1 minOA = "1.0290"
##set1 zone1airflowrate = "2"
##set1 zone2airflowrate = "2.6"
##set1 zone3airflowrate = "2"
##set1 zone4airflowrate = "3.3"
##set1 zone5airflowrate = "3.6"
##set1 zone1reheatcoilcap = "8700"
##set1 zone2reheatcoilcap = "8500"
##set1 zone3reheatcoilcap = "6900"
##set1 zone4reheatcoilcap = "7500"
##set1 zone5reheatcoilcap = "7200"
!Fan Pressure drop, fan and motor efficiency are defined above
Vav_c_nh[]
! VAV_heating.idf

!-----------------------------Plant Script----------------------------
!        There are totally six air cooled type chillers in chilled water plant
!        a variable speed pump is used to control water flow.

##set1 plantflowrate = "0.27535"          !        Plant water flowrate
##set1 plantvolume = "250.0"              !        Plant
volume
```

```
##set1 chilledwatertemp = "7"                                    !        Chilled
Water Supply Temperature
supply_chilled_water_sch[]                                       !        Create
Supply chilled water setpoint Schedule

##set1 chiller_type = "Chiller:CONST COP"                !        Type of chiller
##set1 pumpflowrate = "0.27535"                                  !        Chilled
Water Pump Flow Rate
##set1 pumphead = "300000"                                       !        Chilled
Water Pump Head        (Pa)
##set1 pumppower = "100000"                                      !        Chilled
Water Pump Power (W)
##set1 pumpeff = "0.85"                                          !        Chilled
Water Pump Efficiency (fraction)
##set1 capacity = "1060100"                                      !        Cooling
Capacity for "EACH" Chiller
##set1 chiller_COP = "2.8"                                       !        Chiller
COP (Including Heat Rejection Fans)
##set1 evaflowrate = "0.045892"                                  !
        Evaporator Water Flow rate (m3/s)
##set1 condflowrate = "0.000000001"                      !        Condenser Water
Flowrate (m3/s)
##set1 flowmode = "VariableFlow"                         !        Flow Mode of
Chillers
plantloop[]                                                      !        Create
Plant Loop
chiller[]                                                        !        Create
Chiller Object
pump[]                                                                    !
        Create Pump Object
plant_branch_operation[]                                 !        Create operating
scheme and branch

! ------------------Report------------------------------------------

REPORT,SURFACES,DXF;
REPORT,SURFACES,LINES;
REPORT,SURFACES,DETAILSWITHVERTICES;
REPORT,VARIABLE DICTIONARY;
REPORT,CONSTRUCTION;
!REPORT VARIABLE,*,MEAN AIR TEMPERATURE,HOURLY;
!REPORT VARIABLE,*,Plant Loop Cooling Demand,HOURLY;
!REPORT VARIABLE,*,Zone/Sys Sensible Heating Rate[W],HOURLY;

Report Variable,*,Exterior Horizontal Illuminance From Sky [lux],hourly;
Report Variable,*,Exterior Horizontal Beam Illuminance [lux],hourly;
Report Variable,*,Exterior Beam Normal Illuminance [lux],hourly;
Report Variable,*,Luminous Efficacy of Sky Diffuse Solar Radiation [lum/W],hourly;
Report Variable,*,Luminous Efficacy of Beam Solar Radiation [lum/W],hourly;
Report Variable,*,Sky Clearness for Daylighting Calculation [],hourly;
Report Variable,*,Sky Brightness for Daylighting Calculation [],hourly;
Report Variable,*,Daylight Saving Time Indicator [],hourly;
Report Variable,*,DayType Index [],hourly;
Report Variable,*,Water Mains Temperature [C],hourly;
Report Variable,*,Zone Transmitted Solar[W],hourly;
Report Variable,*,Zone Beam Solar from Exterior Windows[W],hourly;
Report Variable,*,Zone Beam Solar from Interior Windows[W],hourly;
Report Variable,*,Zone Diff Solar from Exterior Windows[W],hourly;
Report Variable,*,Zone Diff Solar from Interior Windows[W],hourly;
Report Variable,*,Zone Window Heat Gain[W],hourly;
Report Variable,*,Zone Window Heat Loss[W],hourly;
Report Variable,*,Surface Ext Sunlit Area [m2],hourly;
Report Variable,*,Surface Ext Sunlit Fraction [],hourly;
Report Variable,*,Surface Ext Solar Incident[W/m2],hourly;
Report Variable,*,Surface Ext Solar Beam Incident[W/m2],hourly;
Report Variable,*,Surface Ext Solar Sky Diffuse Incident[W/m2],hourly;
Report Variable,*,Surface Ext Solar Ground Diffuse Incident[W/m2],hourly;
Report Variable,*,Surface Ext Solar Beam Cosine Of Incidence Angle[],hourly;
Report Variable,*,Surface Ext Solar From Sky Diffuse Refl From Ground[W/m2],hourly;
Report Variable,*,Surface Ext Solar From Sky Diffuse Refl From Obstructions[W/m2],hourly;
Report Variable,*,Surface Ext Beam Sol From Bm-To-Bm Refl From Obstructions[W/m2],hourly;
Report Variable,*,Surface Ext Diff Sol From Bm-To-Diff Refl From Obstructions[W/m2],hourly;
Report Variable,*,Surface Ext Solar From Bm-To-Diff Refl From Ground[W/m2],hourly;
Report Variable,*,Window Solar Absorbed:All Glass Layers[W],hourly;
Report Variable,*,Window Transmitted Solar[W],hourly;
```

Report Variable,*,Window Transmitted Beam Solar[W],hourly;
Report Variable,*,Window Transmitted Diffuse Solar[W],hourly;
Report Variable,*,Window Heat Gain[W],hourly;
Report Variable,*,Window Heat Loss[W],hourly;
Report Variable,*,Window Gap Convective Heat Flow[W],hourly;
Report Variable,*,Window Solar Absorbed:Shading Device[W],hourly;
Report Variable,*,Window System Solar Transmittance[],hourly;
Report Variable,*,Window System Solar Reflectance[],hourly;
Report Variable,*,Window System Solar Absorptance[],hourly;
Report Variable,*,Inside Glass Condensation Flag[],hourly;
Report Variable,*,Inside Frame Condensation Flag[],hourly;
Report Variable,*,Inside Divider Condensation Flag[],hourly;
Report Variable,*,Beam Solar Reflected by Outside Reveal Surfaces[W],hourly;
Report Variable,*,Beam Solar Reflected by Inside Reveal Surfaces[W],hourly;
Report Variable,*,Blind Beam-Beam Solar Transmittance[],hourly;
Report Variable,*,Blind Beam-Diffuse Solar Transmittance[],hourly;
Report Variable,*,Blind Diffuse-Diffuse Solar Transmittance[],hourly;
Report Variable,*,Blind/Glass System Beam-Beam Solar Transmittance[],hourly;
Report Variable,*,Blind/Glass System Diffuse-Diffuse Solar Transmittance[],hourly;
Report Variable,*,Solar Horizontal Profile Angle[degree],hourly;
Report Variable,*,Solar Vertical Profile Angle[degree],hourly;
Report Variable,*,Glass Beam-Beam Solar Transmittance[],hourly;
Report Variable,*,Glass Beam-Diffuse Solar Transmittance[],hourly;
Report Variable,*,Glass Diffuse-Diffuse Solar Transmittance[],hourly;
Report Variable,*,Window Calculation Iterations[],hourly;
Report Variable,*,Beam Sol Intensity from Ext Windows on Inside of Surface[W/m2],hourly;
Report Variable,*,Beam Sol Amount from Ext Windows on Inside of Surface[W],hourly;
Report Variable,*,Diff Sol Intensity from Ext Windows on Inside of Surface[W/m2],hourly;
Report Variable,*,Diff Sol Amount from Ext Windows on Inside of Surface[W],hourly;
Report Variable,*,Beam Sol Intensity from Int Windows on Inside of Surface[W/m2],hourly;
Report Variable,*,Beam Sol Amount from Int Windows on Inside of Surface[W],hourly;
Report Variable,*,Diff Sol Intensity from Int Windows on Inside of Surface[W/m2],hourly;
Report Variable,*,Diff Sol Amount from Int Windows on Inside of Surface[W],hourly;
Report Variable,*,Daylight Illum at Ref Point 1 [lux],hourly;
Report Variable,*,Glare Index at Ref Point 1 [],hourly;
Report Variable,*,Ltg Power Multiplier from Daylighting [],hourly;
Report Variable,*,Daylight Illum at Ref Point 1 from Window[lux],hourly;
Report Variable,*,Daylight Luminance of Window As Viewed From Ref Point 1[cd/m2],hourly;
Report Variable,*,Surface Inside Temperature[C],hourly;
Report Variable,*,Surface Outside Temperature[C],hourly;
Report Variable,*,Surface Int Adjacent Air Temperature [C],hourly;
Report Variable,*,Surface Int Convection Coeff[W/m2-K],hourly;
Report Variable,*,Surface Ext Convection Coeff[W/m2-K],hourly;
Report Variable,*,Surface Ext Rad to Air Coeff[W/m2-K],hourly;
Report Variable,*,Surface Ext Rad to Sky Coeff[W/m2-K],hourly;
Report Variable,*,Surface Ext Rad to Ground Coeff[W/m2-K],hourly;
Report Variable,*,Opaque Surface Inside Face Beam Solar Absorbed[W],hourly;
Report Variable,*,Source Location Temperature[C],hourly;
Report Variable,*,Fraction of Time Shading Device Is On [],hourly;
Report Variable,*,Storm Window On/Off Flag [],hourly;
Report Variable,*,Window Blind Slat Angle [deg],hourly;
Report Variable,*,Mean Radiant Temperature[C],hourly;
Report Variable,*,Zone-Total Internal Latent Gain[J],hourly;
Report Variable,*,Zone-Total Internal Radiant Heat Gain[J],hourly;
Report Variable,*,Zone-Total Internal Convective Heat Gain[J],hourly;
Report Variable,*,Zone-Total Internal Lost Heat Gain[J],hourly;
Report Variable,*,Zone-Total Internal Visible Heat Gain[J],hourly;
Report Variable,*,People-Number of Occupants[],hourly;
Report Variable,*,People-Radiant Heat Gain[J],hourly;
Report Variable,*,People-Convective Heat Gain[J],hourly;
Report Variable,*,People-Sensible Heat Gain[J],hourly;
Report Variable,*,People-Latent Heat Gain[J],hourly;
Report Variable,*,People-Total Heat Gain[J],hourly;
Report Variable,*,Lights-Return Air Heat Gain[J],hourly;
Report Variable,*,Lights-Radiant Heat Gain[J],hourly;
Report Variable,*,Lights-Convective Heat Gain[J],hourly;
Report Variable,*,Lights-Visible Heat Gain[J],hourly;
Report Variable,*,Lights-Total Heat Gain[J],hourly;
Report Variable,*,Electricity:Facility [J],hourly;
Report Variable,*,Electricity:Building [J],hourly;
Report Variable,*,Electricity:Zone:GFSP_N [J],hourly;
Report Variable,*,GeneralLights:Electricity [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:GFSP_N [J],hourly;
Report Variable,*,Lights-Electric Consumption[J],hourly;
Report Variable,*,Electricity:Zone:GFSP_E [J],hourly;

Report Variable,*,GeneralLights:Electricity:Zone:GFSP_E [J],hourly;
Report Variable,*,Electricity:Zone:GFSP_S [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:GFSP_S [J],hourly;
Report Variable,*,Electricity:Zone:GFSP_W [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:GFSP_W [J],hourly;
Report Variable,*,Electricity:Zone:GFSP_I [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:GFSP_I [J],hourly;
Report Variable,*,Electricity:Zone:GFCORE [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:GFCORE [J],hourly;
Report Variable,*,Electricity:Zone:20SP_N [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:20SP_N [J],hourly;
Report Variable,*,Electricity:Zone:20SP_E [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:20SP_E [J],hourly;
Report Variable,*,Electricity:Zone:20SP_S [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:20SP_S [J],hourly;
Report Variable,*,Electricity:Zone:20SP_W [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:20SP_W [J],hourly;
Report Variable,*,Electricity:Zone:20SP_I [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:20SP_I [J],hourly;
Report Variable,*,Electricity:Zone:20CORE [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:20CORE [J],hourly;
Report Variable,*,Electricity:Zone:RFSP_N [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:RFSP_N [J],hourly;
Report Variable,*,Electricity:Zone:RFSP_E [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:RFSP_E [J],hourly;
Report Variable,*,Electricity:Zone:RFSP_S [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:RFSP_S [J],hourly;
Report Variable,*,Electricity:Zone:RFSP_W [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:RFSP_W [J],hourly;
Report Variable,*,Electricity:Zone:RFSP_I [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:RFSP_I [J],hourly;
Report Variable,*,Electricity:Zone:RFCORE [J],hourly;
Report Variable,*,GeneralLights:Electricity:Zone:RFCORE [J],hourly;
Report Variable,*,Electric Eq-Total Heat Gain[J],hourly;
Report Variable,*,Electric Eq-Radiant Heat Gain[J],hourly;
Report Variable,*,Electric Eq-Convective Heat Gain[J],hourly;
Report Variable,*,Electric Eq-Latent Heat Gain[J],hourly;
Report Variable,*,Electric Eq-Lost Heat Gain[J],hourly;
Report Variable,*,Electric Eq-Consumption[J],hourly;
Report Variable,*,Cat00 Electric Eq-Total Heat Gain[J],hourly;
Report Variable,*,Cat00 Electric Eq-Radiant Heat Gain[J],hourly;
Report Variable,*,Cat00 Electric Eq-Convective Heat Gain[J],hourly;
Report Variable,*,Cat00 Electric Eq-Latent Heat Gain[J],hourly;
Report Variable,*,Cat00 Electric Eq-Lost Heat Gain[J],hourly;
Report Variable,*,Cat00_ZoneSource:Electricity [J],hourly;
Report Variable,*,Cat00 Electric Eq-Consumption[J],hourly;
Report Variable,*,Mean Air Temperature[C],hourly;
Report Variable,*,Infiltration-Sensible Heat Loss[J],hourly;
Report Variable,*,Infiltration-Sensible Heat Gain[J],hourly;
Report Variable,*,Infiltration-Volume[m3],hourly;
Report Variable,*,Infiltration-Mass[kg],hourly;
Report Variable,*,Infiltration-Air Change Rate[ach],hourly;
Report Variable,*,EnergyTransfer:Facility [J],hourly;
Report Variable,*,EnergyTransfer:Building [J],hourly;
Report Variable,*,EnergyTransfer:Zone:GFSP_I [J],hourly;
Report Variable,*,Heating:EnergyTransfer [J],hourly;
Report Variable,*,Zone/Sys Sensible Heating Energy[J],hourly;
Report Variable,*,Cooling:EnergyTransfer [J],hourly;
Report Variable,*,Zone/Sys Sensible Cooling Energy[J],hourly;
Report Variable,*,Zone/Sys Sensible Heating Rate[W],hourly;
Report Variable,*,Zone/Sys Sensible Cooling Rate[W],hourly;
Report Variable,*,Zone/Sys Air Temp[C],hourly;
Report Variable,*,Zone Air Humidity Ratio[],hourly;
Report Variable,*,Zone Air Relative Humidity[%],hourly;
Report Variable,*,Zone/Sys Sensible Load Predicted[W],hourly;
Report Variable,*,Zone/Sys Sensible Load to Heating Setpoint Predicted[W],hourly;
Report Variable,*,Zone/Sys Sensible Load to Cooling Setpoint Predicted[W],hourly;
Report Variable,*,Zone/Sys Moisture Load Rate Predicted[kgWater/sec],hourly;
Report Variable,*,Zone/Sys Thermostat Control Type,hourly;
Report Variable,*,Zone/Sys Thermostat Heating Setpoint [C],hourly;
Report Variable,*,Zone/Sys Thermostat Cooling Setpoint [C],hourly;
Report Variable,*,EnergyTransfer:Zone:RFSP_I [J],hourly;
Report Variable,*,EnergyTransfer:Zone:GFCORE [J],hourly;
Report Variable,*,EnergyTransfer:Zone:RFCORE [J],hourly;
Report Variable,*,EnergyTransfer:Zone:GFSP_N [J],hourly;

Report Variable,*,EnergyTransfer:Zone:GFSP_E [J],hourly;
Report Variable,*,EnergyTransfer:Zone:GFSP_S [J],hourly;
Report Variable,*,EnergyTransfer:Zone:GFSP_W [J],hourly;
Report Variable,*,EnergyTransfer:Zone:20SP_N [J],hourly;
Report Variable,*,EnergyTransfer:Zone:20SP_E [J],hourly;
Report Variable,*,EnergyTransfer:Zone:20SP_S [J],hourly;
Report Variable,*,EnergyTransfer:Zone:20SP_W [J],hourly;
Report Variable,*,EnergyTransfer:Zone:RFSP_N [J],hourly;
Report Variable,*,EnergyTransfer:Zone:RFSP_E [J],hourly;
Report Variable,*,EnergyTransfer:Zone:RFSP_S [J],hourly;
Report Variable,*,EnergyTransfer:Zone:RFSP_W [J],hourly;
Report Variable,*,EnergyTransfer:Zone:20SP_I [J],hourly;
Report Variable,*,EnergyTransfer:Zone:20CORE [J],hourly;
Report Variable,*,Zone List Sensible Heating Energy[J],hourly;
Report Variable,*,Zone List Sensible Cooling Energy[J],hourly;
Report Variable,*,Zone List Sensible Heating Rate[W],hourly;
Report Variable,*,Zone List Sensible Cooling Rate[W],hourly;
Report Variable,*,Zone Group Sensible Heating Energy[J],hourly;
Report Variable,*,Zone Group Sensible Cooling Energy[J],hourly;
Report Variable,*,Zone Group Sensible Heating Rate[W],hourly;
Report Variable,*,Zone Group Sensible Cooling Rate[W],hourly;
Report Variable,*,HVACManage Iterations,hourly;
Report Variable,*,Schedule Value [],hourly;
Report Variable,*,Damper Position,hourly;
Report Variable,*,EnergyTransfer:HVAC [J],hourly;
Report Variable,*,HeatingCoils:EnergyTransfer [J],hourly;
Report Variable,*,Heating Coil Energy[J],hourly;
Report Variable,*,Heating Coil Rate[W],hourly;
Report Variable,*,Electricity:HVAC [J],hourly;
Report Variable,*,Heating:Electricity [J],hourly;
Report Variable,*,Heating Coil Electric Consumption [J],hourly;
Report Variable,*,Heating Coil Electric Power [W],hourly;
Report Variable,*,Ventilation Contribution to Heating Load[KJ],hourly;
Report Variable,*,Ventilation Reduction of Heating Load[KJ],hourly;
Report Variable,*,Ventilation No Load Heat Addition[KJ],hourly;
Report Variable,*,Ventilation Contribution to Cooling Load[KJ],hourly;
Report Variable,*,Ventilation Reduction of Cooling Load[KJ],hourly;
Report Variable,*,Ventilation No Load Heat Removal[KJ],hourly;
Report Variable,*,System Cycle On/Off Status,hourly;
Report Variable,*,Max SimAir Iterations,hourly;
Report Variable,*,CoolingCoils:EnergyTransfer [J],hourly;
Report Variable,*,Total Water Cooling Coil Energy[J],hourly;
Report Variable,*,Sensible Water Cooling Coil Energy[J],hourly;
Report Variable,*,Total Water Cooling Coil Rate[W],hourly;
Report Variable,*,Sensible Water Cooling Coil Rate[W],hourly;
Report Variable,*,Cooling Coil Area Wet Fraction,hourly;
Report Variable,*,Fan Electric Power[W],hourly;
Report Variable,*,Fan Delta Temp[C],hourly;
Report Variable,*,Fans:Electricity [J],hourly;
Report Variable,*,Fan Electric Consumption[J],hourly;
Report Variable,*,Plant Loop Cooling Demand[W],hourly;
Report Variable,*,Plant Loop Heating Demand[W],hourly;
Report Variable,*,Plant Loop InletNode Flowrate[kg/s],hourly;
Report Variable,*,Plant Loop InletNode Temperature[C],hourly;
Report Variable,*,Plant Loop OutletNode Temperature[C],hourly;
Report Variable,*,Plant Loop Unmet Demand[W],hourly;
Report Variable,*,Debug Plant Loop Bypass Fraction,hourly;
Report Variable,*,Debug SSOutletNode Flowrate[kg/s],hourly;
Report Variable,*,Chiller Electric Power [W],hourly;
Report Variable,*,Electricity:Plant [J],hourly;
Report Variable,*,Cooling:Electricity [J],hourly;
Report Variable,*,Chiller Electric Consumption [J],hourly;
Report Variable,*,Chiller Evap Heat Trans Rate [W],hourly;
Report Variable,*,EnergyTransfer:Plant [J],hourly;
Report Variable,*,Chillers:EnergyTransfer [J],hourly;
Report Variable,*,Chiller Evap Heat Trans [J],hourly;
Report Variable,*,Chiller Evap Water Inlet Temp [C],hourly;
Report Variable,*,Chiller Evap Water Outlet Temp [C],hourly;
Report Variable,*,Chiller Evap Water Mass Flow Rate [kg/s],hourly;
Report Variable,*,Chiller COP [W/W],hourly;
Report Variable,*,Chiller Cond Heat Trans Rate [W],hourly;
Report Variable,*,HeatRejection:EnergyTransfer [J],hourly;
Report Variable,*,Chiller Cond Heat Trans [J],hourly;
Report Variable,*,Chiller Cond Air Inlet Temp [C],hourly;
Report Variable,*,Pumps:Electricity [J],hourly;

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Report Variable,*,Pump Electric Consumption [J],hourly;
Report Variable,*,Pump Electric Power [W],hourly;
Report Variable,*,Pump Shaft Power[W],hourly;
Report Variable,*,Pump Heat To Fluid[W],hourly;
Report Variable,*,Pump Heat To Fluid Energy[J],hourly;
Report Variable,*,Pump Outlet Temp[C],hourly;
Report Variable,*,Pump Mass Flow Rate[kg/s],hourly;
Report Variable,*,Total Electric Power Purchased [W],hourly;
Report Variable,*,ElectricityPurchased:Facility [J],hourly;
Report Variable,*,ElectricityPurchased:Plant [J],hourly;
Report Variable,*,Cogeneration:ElectricityPurchased [J],hourly;
Report Variable,*,Total Electric Energy Purchased [J],hourly;
Report Variable,*,ElectricitySurplusSold:Facility [J],hourly;
Report Variable,*,ElectricitySurplusSold:Plant [J],hourly;
Report Variable,*,Cogeneration:ElectricitySurplusSold [J],hourly;
Report Variable,*,Total Electric Energy Surplus [J],hourly;
Report Variable,*,Total Building Electric Demand [W],hourly;
Report Variable,*,Total HVAC Electric Demand [W],hourly;
Report Variable,*,Total Electric Demand [W],hourly;
Report Variable,*,Total Electric Power Produced [W],hourly;
Report Variable,*,Total Electric Energy Produced [J],hourly;

Report Meter,Electricity:*,hourly;
Report Meter,Photovoltaic:ElectricityProduced,hourly;
Report Meter,EnergyTransfer:Zone:*,hourly;


!-------------------------Report in Table Format------------------------------
Report:Table:Monthly,
  Building Loads - Cooling,
  ,
  Zone/Sys Sensible Cooling Energy,   SumOrAverage,
  Zone/Sys Sensible Cooling Rate,     Maximum,
  Outdoor Dry Bulb,                   ValueWhenMaxMin,
  Outdoor Wet Bulb,                   ValueWhenMaxMin,
  Zone-Total Internal Latent Gain,    SumOrAverage,
  Zone-Total Internal Latent Gain,    Maximum,
  Outdoor Dry Bulb,                   ValueWhenMaxMin,
  Outdoor Wet Bulb,                   ValueWhenMaxMin;

Report:Table:Monthly,
  Building Loads - Heating,
  ,
  Zone/Sys Sensible Heating Energy,   SumOrAverage,
  Zone/Sys Sensible Heating Rate,     Maximum,
  Outdoor Dry Bulb,                   ValueWhenMaxMin;

Report:Table:Monthly,
  Building Loads - Electric,
  ,
  Lights-Electric Consumption,       SumOrAverage,
  Lights-Electric Consumption,       Maximum,
  Electric Eq-Consumption,           SumOrAverage,
  Electric Eq-Consumption,           Maximum;


 ! Report object inputs for Space Loads Report
 Report:Table:Monthly,
    Space Loads,
    ,
    People-Total Heat Gain,            SumOrAverage,
    Lights-Total Heat Gain,            SumOrAverage,
    Electric Eq-Total Heat Gain,       SumOrAverage,
    Gas Eq-Total Heat Gain,            SumOrAverage,
    Hot Water Eq-Total Heat Gain,      SumOrAverage,
    Steam Eq-Total Heat Gain,          SumOrAverage,
    Other Eq-Total Heat Gain,          SumOrAverage,
    Infiltration-Sensible Heat Gain,   SumOrAverage,
    Infiltration-Sensible Heat Loss,   SumOrAverage;

Report:Table:Monthly,
  End-Use Energy Consumption - Electricity,
  ,
  GeneralLights:Electricity,         SumOrAverage,
  TaskLights:Electricity,            SumOrAverage,
```

```
  ExteriorLights:Electricity,         SumOrAverage,
  Cat00_ZoneSource:Electricity,       SumOrAverage,
  ExteriorEquipment:Electricity,      SumOrAverage,
  Fans:Electricity,                   SumOrAverage,
  Pumps:Electricity,                  SumOrAverage,
  Heating:Electricity,                SumOrAverage,
  Cooling:Electricity,                SumOrAverage,
  HeatRejection:Electricity,          SumOrAverage,
  Humidifier:Electricity,             SumOrAverage,
  HeatRecovery:Electricity,           SumOrAverage,
  DHW:Electricity,                    SumOrAverage,
  Cogeneration:Electricity,           SumOrAverage,
  Miscellaneous:Electricity,          SumOrAverage;

Report:Table:Monthly,
  End-Use Energy Consumption - Natural Gas,
  ,
  ZoneSource:Gas,                     SumOrAverage,
  ExteriorEquipment:Gas,              SumOrAverage,
  Heating:Gas,                        SumOrAverage,
  Cooling:Gas,                        SumOrAverage,
  DHW:Gas,                            SumOrAverage,
  Cogeneration:Gas,                   SumOrAverage,
  Miscellaneous:Gas,                  SumOrAverage;

 Report:Table:Monthly,
  End-Use Energy Consumption - Diesel,
  ,
  ExteriorEquipment:Diesel,           SumOrAverage,
  Cooling:Diesel,                     SumOrAverage,
  Heating:Diesel,                     SumOrAverage,
  DHW:Diesel,                         SumOrAverage,
  Cogeneration:Diesel,                SumOrAverage;

 Report:Table:Monthly,
  End-Use Energy Consumption - Fuel Oil,
  ,
  ExteriorEquipment:FuelOil#1,        SumOrAverage,
  Cooling:FuelOil#1,                  SumOrAverage,
  Heating:FuelOil#1,                  SumOrAverage,
  DHW:FuelOil#1,                      SumOrAverage,
  Cogeneration:FuelOil#1,             SumOrAverage,
  ExteriorEquipment:FuelOil#2,        SumOrAverage,
  Cooling:FuelOil#2,                  SumOrAverage,
  Heating:FuelOil#2,                  SumOrAverage,
  DHW:FuelOil#2,                      SumOrAverage,
  Cogeneration:FuelOil#2,             SumOrAverage;

Report:Table:Monthly,
  End-Use Energy Consumption - Coal,
  ,
  ExteriorEquipment:Coal,             SumOrAverage,
  Heating:Coal,                       SumOrAverage,
  DHW:Coal,                           SumOrAverage;

Report:Table:Monthly,
  End-Use Energy Consumption - Propane,
  ,
  ExteriorEquipment:Propane,          SumOrAverage,
  Cooling:Propane,                    SumOrAverage,
  Heating:Propane,                    SumOrAverage,
  DHW:Propane,                        SumOrAverage,
  Cogeneration:Propane,               SumOrAverage;

Report:Table:Monthly,
  End-Use Energy Consumption - Gasoline,
  ,
  ExteriorEquipment:Gasoline,         SumOrAverage,
  Cooling:Gasoline,                   SumOrAverage,
  Heating:Gasoline,                   SumOrAverage,
  DHW:Gasoline,                       SumOrAverage,
  Cogeneration:Gasoline,              SumOrAverage;

Report:Table:Monthly,
  Peak Energy End-Use - Electricity Part 1,
```

```
  ,
  GeneralLights:Electricity,           Maximum,
  TaskLights:Electricity,              Maximum,
  ExteriorLights:Electricity,          Maximum,
  Cat00_ZoneSource:Electricity,        Maximum,
  ExteriorEquipment:Electricity,       Maximum,
  Fans:Electricity,                    Maximum,
  Pumps:Electricity,                   Maximum,
  Heating:Electricity,                 Maximum;

Report:Table:Monthly,
  Peak Energy End-Use - Electricity Part 2,
  ,
  Cooling:Electricity,                 Maximum,
  HeatRejection:Electricity,           Maximum,
  Humidifier:Electricity,              Maximum,
  HeatRecovery:Electricity,            Maximum,
  DHW:Electricity,                     Maximum,
  Cogeneration:Electricity,            Maximum,
  Miscellaneous:Electricity,           Maximum;


##include gen_info.idf
!-Generator IDFEditor 1.24
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-     Use '!' comments if they need to be retained when using the IDFEditor.
!-   ===========  ALL OBJECTS IN CLASS: VERSION ===========

VERSION,
    1.2.2.030;              !- Version Identifier

!-   ===========  ALL OBJECTS IN CLASS: BUILDING ===========

BUILDING,
    Generic Office Building, !- Building Name
    0,                      !- North Axis {deg}
    City,                   !- Terrain
    0.04,                   !- Loads Convergence Tolerance Value {W}
    0.4,                    !- Temperature Convergence Tolerance Value {deltaC}
    FullExterior,           !- Solar Distribution
    25;                     !- Maximum Number of Warmup Days

!-   ===========  ALL OBJECTS IN CLASS: TIMESTEP IN HOUR ===========

TIMESTEP IN HOUR,
    6;                      !- Time Step in Hour

!-   ===========  ALL OBJECTS IN CLASS: INSIDE CONVECTION ALGORITHM ===========

INSIDE CONVECTION ALGORITHM,
    Detailed;               !- InsideConvectionValue

!-   ===========  ALL OBJECTS IN CLASS: OUTSIDE CONVECTION ALGORITHM ===========

OUTSIDE CONVECTION ALGORITHM,
    Detailed;               !- OutsideConvectionValue

!-   ===========  ALL OBJECTS IN CLASS: SOLUTION ALGORITHM ===========

SOLUTION ALGORITHM,
    CTF;                    !- SolutionAlgo

!-   ===========  ALL OBJECTS IN CLASS: SHADOWING CALCULATIONS ===========

SHADOWING CALCULATIONS,
    1;                      !- Period_for_calculations

!-   ===========  ALL OBJECTS IN CLASS: AIRFLOW MODEL ===========

Airflow Model,
    Simple;                 !- AirFlowModelValue

!-   ===========  ALL OBJECTS IN CLASS: ZONE VOLUME CAPACITANCE MULTIPLIER ===========

ZONE VOLUME CAPACITANCE MULTIPLIER,
```

```
    1;                  !- Capacitance Multiplier

!-   ===========  ALL OBJECTS IN CLASS: RUN CONTROL ===========

RUN CONTROL,
    No,                 !- Do the zone sizing calculation
    Yes,                !- Do the system sizing calculation
    No,                 !- Do the plant sizing calculation
    Yes,                !- Do the design day simulations
    No;                 !- Do the weather file simulation

!-   ===========  ALL OBJECTS IN CLASS: RUNPERIOD ===========

RunPeriod,
    1,                  !- Begin Month
    1,                  !- Begin Day Of Month
    12,                 !- End Month
    31,                 !- End Day Of Month
    ,                   !- Day Of Week For Start Day
    No,                 !- Use WeatherFile Holidays/Special Days
    No,                 !- Use WeatherFile DaylightSavingPeriod
    ,                   !- Apply Weekend Holiday Rule
    ,                   !- Use WeatherFile Rain Indicators
    ;                   !- Use WeatherFile Snow Indicators

!-   ===========  ALL OBJECTS IN CLASS: GROUNDTEMPERATURES ===========

GroundTemperatures,
    18.3,               !- January Ground Temperature {C}
    18,                 !- February Ground Temperature {C}
    19.8,               !- March Ground Temperature {C}
    22.6,               !- April Ground Temperature {C}
    25.8,               !- May Ground Temperature {C}
    28.1,               !- June Ground Temperature {C}
    29.3,               !- July Ground Temperature {C}
    29.3,               !- August Ground Temperature {C}
    28.4,               !- September Ground Temperature {C}
    26.4,               !- October Ground Temperature {C}
    22.8,               !- November Ground Temperature {C}
    19.6;               !- December Ground Temperature {C}

!-   ===========  ALL OBJECTS IN CLASS: LOCATION ===========

Location,
    Hong Kong,          !- LocationName
    22.3,               !- Latitude {deg}
    114.2,              !- Longitude {deg}
    8,                  !- TimeZone {hr}
    33;                 !- Elevation {m}

!-   ===========  ALL OBJECTS IN CLASS: SURFACEGEOMETRY ===========

SurfaceGeometry,
    UpperLeftCorner,    !- SurfaceStartingPosition
    CounterClockWise,   !- VertexEntry
    relative;           !- CoordinateSystem

##include design_conditions.idf
!-Generator IDFEditor 1.13
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-     Use '!' comments if they need to be retained when using the IDFEditor.

!-   ===========  ALL OBJECTS IN CLASS: DESIGNDAY ===========

DesignDay,
    SummerDesignDay,    !- DesignDayName
    33.5,               !- Maximum Dry-Bulb Temperature {C}
    5,                  !- Daily Temperature Range {deltaC}
    27,                 !- Humidity Indicating Temperature at Max Temp {C}
    100530,             !- Barometric Pressure {Pa}
    2,                  !- Wind Speed {m/s}
    90,                 !- Wind Direction {deg}
    1,                  !- Sky Clearness
    0,                  !- Rain Indicator
    0,                  !- Snow Indicator
```

```
   21,                  !- Day Of Month
   7,                  !- Month
   SummerDesignDay,        !- Day Type
   0,                  !- Daylight Saving Time Indicator
   Wet-Bulb;              !- Humidity Indicating Temperature Type

DesignDay,
   WinterDesignDay,        !- DesignDayName
   8.3,                  !- Maximum Dry-Bulb Temperature {C}
   5,                  !- Daily Temperature Range {deltaC}
   5,                  !- Humidity Indicating Temperature at Max Temp {C}
   102020,              !- Barometric Pressure {Pa}
   6.8,                  !- Wind Speed {m/s}
   70,                  !- Wind Direction {deg}
   1,                  !- Sky Clearness
   0,                  !- Rain Indicator
   0,                  !- Snow Indicator
   21,                  !- Day Of Month
   1,                  !- Month
   WinterDesignDay,        !- Day Type
   0,                  !- Daylight Saving Time Indicator
   Wet-Bulb;              !- Humidity Indicating Temperature Type

##include multiplier.idf
!-Generator IDFEditor 1.20
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-      Use '!' comments if they need to be retained when using the IDFEditor.

!-   ===========  ALL OBJECTS IN CLASS: ZONE LIST ======

ZONE LIST,
   GF FLOOR LIST,                  !- Zone List Name
   GFSP_N,                  !- Zone Name 1
   GFSP_E,                  !- Zone Name 2
   GFSP_S,                  !- Zone Name 3
   GFSP_W,                  !- Zone Name 4
   GFSP_I,                  !- Zone Name 5
   GFCORE;                  !- zone Name 6

ZONE LIST,
   20th FLOOR LIST,                  !- Zone List Name
   20SP_N,                  !- Zone Name 1
   20SP_E,                  !- Zone Name 2
   20SP_S,                  !- Zone Name 3
   20SP_W,                  !- Zone Name 4
   20SP_I,                  !- Zone Name 5
   20CORE;                  !- zone Name 6

ZONE LIST,
   RF LIST,                  !- Zone List Name
   RFSP_N,                  !- Zone Name 1
   RFSP_E,                  !- Zone Name 2
   RFSP_S,                  !- Zone Name 3
   RFSP_W,                  !- Zone Name 4
   RFSP_I,                  !- Zone Name 5
   RFCORE;                  !- zone Name 6

!-   ===========  ALL OBJECTS IN CLASS: ZONE GROUP======

ZONE GROUP,
   GF FLOOR,                              !- Zone Group Name
   GF FLOOR LIST,                  !- Zone List Name
   1;                              !- Zone List Multiplier

ZONE GROUP,
   20th FLOOR,                              !- Zone Group Name
   20th FLOOR LIST,                  !- Zone List Name
   1;                              !- Zone List Multiplier

ZONE GROUP,
   RF FLOOR,                              !- Zone Group Name
   RF LIST,                  !- Zone List Name
   1;                              !- Zone List Multiplier
```

```
##externalzone.idf
!-Generator IDFEditor 1.13
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-     Use '!' comments if they need to be retained when using the IDFEditor.

##def zone_GF[]
!-   ===========  ALL OBJECTS IN CLASS: ZONE ===========

!               zonename[]               Name of zone
!               azi_ang[]                angle of rotation
!               EWALL-HL[]                              high level of external wall
!               EWALL-LL[]                              low level of external wall
!               WIN-HL[]                 high level of window
!               WIN-LL[]                 low level of window
!               IWALL-HL[]                              high level of internal wall
!               IWALL-LL[]                              low level of internal wall
!               ceilheight[]             height of ceiling
!               shading_control[]        Shading Control Type
!               ext_wall_type[]                         External Wall Construction Type
!               int_wall_type[]                         Internal Wall Construction Type
!               window_glazing_type[]    Window Construction Type
!               floor_const_type[]       Typical Floor Construction Type
!               ceiling_const_type[]     Ceiling Construction Type
!               ground_const_type[]      Ground Construction Type
!               roof_const_type[]        Roof Construction Type

ZONE,
   zonename[],            !- Zone Name
   azi_ang[],             !- Relative North (to building) {deg}
   0,                     !- X Origin {m}
   0,                     !- Y Origin {m}
   0,                     !- Z Origin {m}
   1,                     !- Type
   1,                     !- Multiplier
   ceilheight[],                !- Ceiling Height {m}
   343.125;               !- Volume {m3}

!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER ===========

Surface:HeatTransfer,
  zonename[]:EWALL,         !- User Supplied Surface Name
  WALL,                   !- Surface Type
  ext_wall_type[],               !- Construction Name of the Surface
  zonename[],               !- InsideFaceEnvironment
  ExteriorEnvironment,    !- OutsideFaceEnvironment
  ,                       !- OutsideFaceEnvironment Object
  SunExposed,             !- Sun Exposure
  WindExposed,            !- Wind Exposure
  0.5,                    !- View Factor to Ground
  4,                      !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  17.5,                     !- Vertex 1 X-coordinate {m}
  17.5,                     !- Vertex 1 Y-coordinate {m}
  EWALL-HL[],                  !- Vertex 1 Z-coordinate {m}
  17.5,                     !- Vertex 2 X-coordinate {m}
  17.5,                     !- Vertex 2 Y-coordinate {m}
  EWALL-LL[],                  !- Vertex 2 Z-coordinate {m}
  -17.5,                    !- Vertex 3 X-coordinate {m}
  17.5,                     !- Vertex 3 Y-coordinate {m}
  EWALL-LL[],                  !- Vertex 3 Z-coordinate {m}
  -17.5,                    !- Vertex 4 X-coordinate {m}
  17.5,                     !- Vertex 4 Y-coordinate {m}
  EWALL-HL[];                  !- Vertex 4 Z-coordinate {m}


!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER ===========
!- zonename[]       name of zone
!- IWALL1-outsidefaceenv[]  outside face environment of internal wall1
!- IWALL2-outsidefaceenv[]  outside face environment of internal wall2
!- IWALL3-outsidefaceenv[]  outside face environment of internal wall3

Surface:HeatTransfer,
  zonename[]:IWALL-1,         !- User Supplied Surface Name
  WALL,                   !- Surface Type
  int_wall_type[],              !- Construction Name of the Surface
  zonename[],               !- InsideFaceEnvironment
```

```
  OtherZone,             !- OutsideFaceEnvironment
  IWALL1-outsidefaceenv[],         !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0.5,                   !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  13,                    !- Vertex 1 X-coordinate {m}
  13,                    !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],                  !- Vertex 1 Z-coordinate {m}
  13,                    !- Vertex 2 X-coordinate {m}
  13,                    !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],                  !- Vertex 2 Z-coordinate {m}
  17.5,                  !- Vertex 3 X-coordinate {m}
  17.5,                  !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],                  !- Vertex 3 Z-coordinate {m}
  17.5,                  !- Vertex 4 X-coordinate {m}
  17.5,                  !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];                  !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  zonename[]:IWALL-2,         !- User Supplied Surface Name
  WALL,                  !- Surface Type
  int_wall_type[],              !- Construction Name of the Surface
  zonename[],                !- InsideFaceEnvironment
  OtherZone,             !- OutsideFaceEnvironment
  IWALL2-outsidefaceenv[],         !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0.5,                   !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -13,                   !- Vertex 1 X-coordinate {m}
  13,                    !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],                  !- Vertex 1 Z-coordinate {m}
  -13,                   !- Vertex 2 X-coordinate {m}
  13,                    !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],                  !- Vertex 2 Z-coordinate {m}
  13,                    !- Vertex 3 X-coordinate {m}
  13,                    !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],                  !- Vertex 3 Z-coordinate {m}
  13,                    !- Vertex 4 X-coordinate {m}
  13,                    !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];                  !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  zonename[]:IWALL-3,         !- User Supplied Surface Name
  WALL,                  !- Surface Type
  int_wall_type[],              !- Construction Name of the Surface
  zonename[],                !- InsideFaceEnvironment
  OtherZone,             !- OutsideFaceEnvironment
  IWALL3-outsidefaceenv[],         !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0.5,                   !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -17.5,                 !- Vertex 1 X-coordinate {m}
  17.5,                  !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],                  !- Vertex 1 Z-coordinate {m}
  -17.5,                 !- Vertex 2 X-coordinate {m}
  17.5,                  !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],                  !- Vertex 2 Z-coordinate {m}
  -13,                   !- Vertex 3 X-coordinate {m}
  13,                    !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],                  !- Vertex 3 Z-coordinate {m}
  -13,                   !- Vertex 4 X-coordinate {m}
  13,                    !- Vertex 4 Y-coordinate {m}
  IWALL-HL[] ;                 !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer:Sub,
   zonename[]:WIN,           !- User Supplied Surface Name
   WINDOW,                 !- Surface Type
   window_glazing_type[],  !- Construction Name of the Surface
   zonename[]:EWALL,         !- Base Surface Name
   ,                     !- OutsideFaceEnvironment Object
   0.5,                   !- View Factor to Ground
   shading_control[],  !- Name of shading control
```

```
    ,                    !- WindowFrameAndDivider Name
    1,                   !- Multiplier
    4,                   !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    17.5,                !- Vertex 1 X-coordinate {m}
    17.5,                !- Vertex 1 Y-coordinate {m}
    WIN-HL[],            !- Vertex 1 Z-coordinate {m}
    17.5,                !- Vertex 2 X-coordinate {m}
    17.5,                !- Vertex 2 Y-coordinate {m}
    WIN-LL[],            !- Vertex 2 Z-coordinate {m}
    -17.5,               !- Vertex 3 X-coordinate {m}
    17.5,                !- Vertex 3 Y-coordinate {m}
    WIN-LL[],            !- Vertex 3 Z-coordinate {m}
    -17.5,               !- Vertex 4 X-coordinate {m}
    17.5,                !- Vertex 4 Y-coordinate {m}
    WIN-HL[];            !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
    zonename[]:FLOOR,    !- User Supplied Surface Name
    FLOOR,               !- Surface Type
    ground_const_type[], !- Construction Name of the Surface
    zonename[],          !- InsideFaceEnvironment
    Ground,              !- OutsideFaceEnvironment
    ,                    !- OutsideFaceEnvironment Object
    NoSun,               !- Sun Exposure
    NoWind,              !- Wind Exposure
    1,                   !- View Factor to Ground
    4,                   !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
    -13,                 !- Vertex 1 X-coordinate {m}
    13,                  !- Vertex 1 Y-coordinate {m}
    0,                   !- Vertex 1 Z-coordinate {m}
    -17.5,               !- Vertex 2 X-coordinate {m}
    17.5,                !- Vertex 2 Y-coordinate {m}
    0,                   !- Vertex 2 Z-coordinate {m}
    17.5,                !- Vertex 3 X-coordinate {m}
    17.5,                !- Vertex 3 Y-coordinate {m}
    0,                   !- Vertex 3 Z-coordinate {m}
    13,                  !- Vertex 4 X-coordinate {m}
    13,                  !- Vertex 4 Y-coordinate {m}
    0;                   !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
    zonename[]:CEILING,  !- User Supplied Surface Name
    CEILING,             !- Surface Type
    ceiling_const_type[], !- Construction Name of the Surface
    zonename[],          !- InsideFaceEnvironment
    OtherZone,           !- OutsideFaceEnvironment
    zonename[]:CEILING,  !- OutsideFaceEnvironment Object
    NoSun,               !- Sun Exposure
    NoWind,              !- Wind Exposure
    0,                   !- View Factor to Ground
    4,                   !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
    -17.5,               !- Vertex 1 X-coordinate {m}
    17.5,                !- Vertex 1 Y-coordinate {m}
    ceilheight[],        !- Vertex 1 Z-coordinate {m}
    -13,                 !- Vertex 2 X-coordinate {m}
    13,                  !- Vertex 2 Y-coordinate {m}
    ceilheight[],        !- Vertex 2 Z-coordinate {m}
    13,                  !- Vertex 3 X-coordinate {m}
    13,                  !- Vertex 3 Y-coordinate {m}
    ceilheight[],        !- Vertex 3 Z-coordinate {m}
    17.5,                !- Vertex 4 X-coordinate {m}
    17.5,                !- Vertex 4 Y-coordinate {m}
    ceilheight[];        !- Vertex 4 Z-coordinate {m}

##enddef

##def zone_20[]
!-   ===========  ALL OBJECTS IN CLASS: ZONE ===========
!-   zonename[]              Name of zone
!-   azi_ang[]               angle of rotation
!-   typicalfloor-z-orgin[]  z-orgin of typical floor

ZONE,
    zonename[],          !- Zone Name
    azi_ang[],           !- Relative North (to building) {deg}
```

```
  0,                  !- X Origin {m}
  0,                  !- Y Origin {m}
  typicalfloor-z-origin[],                  !- Z Origin {m}
  1,                  !- Type
  38,                  !- Multiplier
  ceilheight[],                !- Ceiling Height {m}
  343.125;             !- Volume {m3}

!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER ===========

Surface:HeatTransfer,
  zonename[]:EWALL,        !- User Supplied Surface Name
  WALL,                !- Surface Type
  ext_wall_type[],               !- Construction Name of the Surface
  zonename[],              !- InsideFaceEnvironment
  ExteriorEnvironment,    !- OutsideFaceEnvironment
  ,                  !- OutsideFaceEnvironment Object
  SunExposed,            !- Sun Exposure
  WindExposed,           !- Wind Exposure
  0.5,                 !- View Factor to Ground
  4,                  !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  17.5,                !- Vertex 1 X-coordinate {m}
  17.5,                !- Vertex 1 Y-coordinate {m}
  EWALL-HL[],                !- Vertex 1 Z-coordinate {m}
  17.5,                !- Vertex 2 X-coordinate {m}
  17.5,                !- Vertex 2 Y-coordinate {m}
  EWALL-LL[],                 !- Vertex 2 Z-coordinate {m}
  -17.5,                !- Vertex 3 X-coordinate {m}
  17.5,                !- Vertex 3 Y-coordinate {m}
  EWALL-LL[],                 !- Vertex 3 Z-coordinate {m}
  -17.5,                !- Vertex 4 X-coordinate {m}
  17.5,                !- Vertex 4 Y-coordinate {m}
  EWALL-HL[];                !- Vertex 4 Z-coordinate {m}

!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER ===========
!- zonename[]      name of zone
!- IWALL1-outsidefaceenv[]  outside face environment of internal wall1
!- IWALL2-outsidefaceenv[]  outside face environment of internal wall2
!- IWALL3-outsidefaceenv[]  outside face environment of internal wall3

Surface:HeatTransfer,
  zonename[]:IWALL-1,        !- User Supplied Surface Name
  WALL,                !- Surface Type
  int_wall_type[],              !- Construction Name of the Surface
  zonename[],              !- InsideFaceEnvironment
  OtherZone,            !- OutsideFaceEnvironment
  IWALL1-outsidefaceenv[],        !- OutsideFaceEnvironment Object
  NoSun,               !- Sun Exposure
  NoWind,               !- Wind Exposure
  0.5,                 !- View Factor to Ground
  4,                  !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  13,               !- Vertex 1 X-coordinate {m}
  13,               !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],               !- Vertex 1 Z-coordinate {m}
  13,               !- Vertex 2 X-coordinate {m}
  13,               !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],                !- Vertex 2 Z-coordinate {m}
  17.5,                !- Vertex 3 X-coordinate {m}
  17.5,                !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],                !- Vertex 3 Z-coordinate {m}
  17.5,                !- Vertex 4 X-coordinate {m}
  17.5,                !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];               !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  zonename[]:IWALL-2,        !- User Supplied Surface Name
  WALL,                !- Surface Type
  int_wall_type[],              !- Construction Name of the Surface
  zonename[],              !- InsideFaceEnvironment
  OtherZone,            !- OutsideFaceEnvironment
  IWALL2-outsidefaceenv[],        !- OutsideFaceEnvironment Object
  NoSun,               !- Sun Exposure
  NoWind,               !- Wind Exposure
  0.5,                 !- View Factor to Ground
  4,                  !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
```

```
  -13,                   !- Vertex 1 X-coordinate {m}
  13,                    !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],            !- Vertex 1 Z-coordinate {m}
  -13,                   !- Vertex 2 X-coordinate {m}
  13,                    !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],            !- Vertex 2 Z-coordinate {m}
  13,                    !- Vertex 3 X-coordinate {m}
  13,                    !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],            !- Vertex 3 Z-coordinate {m}
  13,                    !- Vertex 4 X-coordinate {m}
  13,                    !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];            !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  zonename[]:IWALL-3,    !- User Supplied Surface Name
  WALL,                  !- Surface Type
  int_wall_type[],       !- Construction Name of the Surface
  zonename[],            !- InsideFaceEnvironment
  OtherZone,             !- OutsideFaceEnvironment
  IWALL3-outsidefaceenv[],   !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0.5,                   !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -17.5,                 !- Vertex 1 X-coordinate {m}
  17.5,                  !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],            !- Vertex 1 Z-coordinate {m}
  -17.5,                 !- Vertex 2 X-coordinate {m}
  17.5,                  !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],            !- Vertex 2 Z-coordinate {m}
  -13,                   !- Vertex 3 X-coordinate {m}
  13,                    !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],            !- Vertex 3 Z-coordinate {m}
  -13,                   !- Vertex 4 X-coordinate {m}
  13,                    !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];            !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer:Sub,
   zonename[]:WIN,       !- User Supplied Surface Name
   WINDOW,               !- Surface Type
   window_glazing_type[],  !- Construction Name of the Surface
   zonename[]:EWALL,     !- Base Surface Name
   ,                     !- OutsideFaceEnvironment Object
   0.5,                  !- View Factor to Ground
   shading_control[],  !- Name of shading control
   ,                     !- WindowFrameAndDivider Name
   1,                    !- Multiplier
   4,                    !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
   17.5,                 !- Vertex 1 X-coordinate {m}
   17.5,                 !- Vertex 1 Y-coordinate {m}
   WIN-HL[],             !- Vertex 1 Z-coordinate {m}
   17.5,                 !- Vertex 2 X-coordinate {m}
   17.5,                 !- Vertex 2 Y-coordinate {m}
   WIN-LL[],             !- Vertex 2 Z-coordinate {m}
   -17.5,                !- Vertex 3 X-coordinate {m}
  17.5,                  !- Vertex 3 Y-coordinate {m}
   WIN-LL[],             !- Vertex 3 Z-coordinate {m}
   -17.5,                !- Vertex 4 X-coordinate {m}
   17.5,                 !- Vertex 4 Y-coordinate {m}
   WIN-HL[];             !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
   zonename[]:FLOOR,     !- User Supplied Surface Name
   FLOOR,                !- Surface Type
   floor_const_type[],   !- Construction Name of the Surface
   zonename[],           !- InsideFaceEnvironment
   OtherZone,            !- OutsideFaceEnvironment
   zonename[]:FLOOR,     !- OutsideFaceEnvironment Object
   NoSun,                !- Sun Exposure
   NoWind,               !- Wind Exposure
   1,                    !- View Factor to Ground
   4,                    !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
   -13,                  !- Vertex 1 X-coordinate {m}
   13,                   !- Vertex 1 Y-coordinate {m}
   0,                    !- Vertex 1 Z-coordinate {m}
```

```
  -17.5,                !- Vertex 2 X-coordinate {m}
  17.5,                 !- Vertex 2 Y-coordinate {m}
  0,                    !- Vertex 2 Z-coordinate {m}
  17.5,                 !- Vertex 3 X-coordinate {m}
  17.5,                 !- Vertex 3 Y-coordinate {m}
  0,                    !- Vertex 3 Z-coordinate {m}
  13,                   !- Vertex 4 X-coordinate {m}
  13,                   !- Vertex 4 Y-coordinate {m}
  0;                    !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  zonename[]:CEILING,          !- User Supplied Surface Name
  CEILING,                !- Surface Type
  ceiling_const_type[],               !- Construction Name of the Surface
  zonename[],                 !- InsideFaceEnvironment
  OtherZone,              !- OutsideFaceEnvironment
  zonename[]:CEILING,            !- OutsideFaceEnvironment Object
  NoSun,                  !- Sun Exposure
  NoWind,                 !- Wind Exposure
  0,                    !- View Factor to Ground
  4,                    !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -17.5,                !- Vertex 1 X-coordinate {m}
  17.5,                 !- Vertex 1 Y-coordinate {m}
  ceilheight[],                !- Vertex 1 Z-coordinate {m}
  -13,                  !- Vertex 2 X-coordinate {m}
  13,                   !- Vertex 2 Y-coordinate {m}
  ceilheight[],                !- Vertex 2 Z-coordinate {m}
  13,                   !- Vertex 3 X-coordinate {m}
  13,                   !- Vertex 3 Y-coordinate {m}
  ceilheight[],                !- Vertex 3 Z-coordinate {m}
  17.5,                 !- Vertex 4 X-coordinate {m}
  17.5,                 !- Vertex 4 Y-coordinate {m}
  ceilheight[];                !- Vertex 4 Z-coordinate {m}

##enddef

##def zone_RF[]
!-   ===========  ALL OBJECTS IN CLASS: ZONE ===========
!-   zonename[]            Name of zone
!-   azi_ang[]             angle of rotation
!-  RF-z-orgin[]           z-orgin of RF

ZONE,
  zonename[],             !- Zone Name
  azi_ang[],              !- Relative North (to building) {deg}
  0,                    !- X Origin {m}
  0,                    !- Y Origin {m}
  RF-z-origin[],                 !- Z Origin {m}
  1,                    !- Type
  1,                    !- Multiplier
  ceilheight[],                !- Ceiling Height {m}
  343.125;              !- Volume {m3}

!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER ===========

Surface:HeatTransfer,
  zonename[]:EWALL,         !- User Supplied Surface Name
  WALL,                 !- Surface Type
  ext_wall_type[],                !- Construction Name of the Surface
  zonename[],               !- InsideFaceEnvironment
  ExteriorEnvironment,     !- OutsideFaceEnvironment
  ,                    !- OutsideFaceEnvironment Object
  SunExposed,            !- Sun Exposure
  WindExposed,           !- Wind Exposure
  0.5,                  !- View Factor to Ground
  4,                    !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  17.5,                 !- Vertex 1 X-coordinate {m}
  17.5,                 !- Vertex 1 Y-coordinate {m}
  EWALL-HL[],                !- Vertex 1 Z-coordinate {m}
  17.5,                 !- Vertex 2 X-coordinate {m}
  17.5,                 !- Vertex 2 Y-coordinate {m}
  EWALL-LL[],                  !- Vertex 2 Z-coordinate {m}
  -17.5,                !- Vertex 3 X-coordinate {m}
  17.5,                 !- Vertex 3 Y-coordinate {m}
  EWALL-LL[],                  !- Vertex 3 Z-coordinate {m}
```

```
  -17.5,                    !- Vertex 4 X-coordinate {m}
  17.5,                 !- Vertex 4 Y-coordinate {m}
  EWALL-HL[];                   !- Vertex 4 Z-coordinate {m}


!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER ===========
!- zonename[]       name of zone
!- IWALL1-outsidefaceenv[]  outside face environment of internal wall1
!- IWALL2-outsidefaceenv[]  outside face environment of internal wall2
!- IWALL3-outsidefaceenv[]  outside face environment of internal wall3

Surface:HeatTransfer,
  zonename[]:IWALL-1,         !- User Supplied Surface Name
  WALL,                  !- Surface Type
  int_wall_type[],              !- Construction Name of the Surface
  zonename[],                !- InsideFaceEnvironment
  OtherZone,             !- OutsideFaceEnvironment
  IWALL1-outsidefaceenv[],         !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0.5,                   !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  13,                !- Vertex 1 X-coordinate {m}
  13,                !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],                  !- Vertex 1 Z-coordinate {m}
  13,                !- Vertex 2 X-coordinate {m}
  13,                !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],                   !- Vertex 2 Z-coordinate {m}
  17.5,                 !- Vertex 3 X-coordinate {m}
  17.5,                 !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],                   !- Vertex 3 Z-coordinate {m}
  17.5,                 !- Vertex 4 X-coordinate {m}
  17.5,                 !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];                  !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  zonename[]:IWALL-2,         !- User Supplied Surface Name
  WALL,                  !- Surface Type
  int_wall_type[],              !- Construction Name of the Surface
  zonename[],                !- InsideFaceEnvironment
  OtherZone,             !- OutsideFaceEnvironment
  IWALL2-outsidefaceenv[],         !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0.5,                   !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -13,                !- Vertex 1 X-coordinate {m}
  13,                !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],                  !- Vertex 1 Z-coordinate {m}
  -13,                !- Vertex 2 X-coordinate {m}
  13,                !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],                   !- Vertex 2 Z-coordinate {m}
  13,                !- Vertex 3 X-coordinate {m}
  13,                !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],                   !- Vertex 3 Z-coordinate {m}
  13,                !- Vertex 4 X-coordinate {m}
  13,                !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];                  !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  zonename[]:IWALL-3,         !- User Supplied Surface Name
  WALL,                  !- Surface Type
  int_wall_type[],              !- Construction Name of the Surface
  zonename[],                !- InsideFaceEnvironment
  OtherZone,             !- OutsideFaceEnvironment
  IWALL3-outsidefaceenv[],         !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0.5,                   !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -17.5,                 !- Vertex 1 X-coordinate {m}
  17.5,                 !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],                  !- Vertex 1 Z-coordinate {m}
  -17.5,                 !- Vertex 2 X-coordinate {m}
  17.5,                 !- Vertex 2 Y-coordinate {m}
```

```
  IWALL-LL[],                !- Vertex 2 Z-coordinate {m}
  -13,                !- Vertex 3 X-coordinate {m}
  13,                !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],                !- Vertex 3 Z-coordinate {m}
  -13,                !- Vertex 4 X-coordinate {m}
  13,                !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];                !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer:Sub,
   zonename[]:WIN,           !- User Supplied Surface Name
   WINDOW,               !- Surface Type
   window_glazing_type[],  !- Construction Name of the Surface
   zonename[]:EWALL,        !- Base Surface Name
   ,                  !- OutsideFaceEnvironment Object
   0.5,                !- View Factor to Ground
   shading_control[],  !- Name of shading control
   ,                  !- WindowFrameAndDivider Name
   1,                 !- Multiplier
   4,                 !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
   17.5,                 !- Vertex 1 X-coordinate {m}
   17.5,                 !- Vertex 1 Y-coordinate {m}
   WIN-HL[],                 !- Vertex 1 Z-coordinate {m}
   17.5,                 !- Vertex 2 X-coordinate {m}
   17.5,                 !- Vertex 2 Y-coordinate {m}
   WIN-LL[],                 !- Vertex 2 Z-coordinate {m}
   -17.5,                 !- Vertex 3 X-coordinate {m}
  17.5,                 !- Vertex 3 Y-coordinate {m}
   WIN-LL[],                 !- Vertex 3 Z-coordinate {m}
   -17.5,                 !- Vertex 4 X-coordinate {m}
   17.5,                 !- Vertex 4 Y-coordinate {m}
   WIN-HL[];                 !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
   zonename[]:FLOOR,           !- User Supplied Surface Name
   FLOOR,                !- Surface Type
   floor_const_type[],                !- Construction Name of the Surface
   zonename[],                !- InsideFaceEnvironment
   OtherZone,             !- OutsideFaceEnvironment
   zonename[]:FLOOR,          !- OutsideFaceEnvironment Object
   NoSun,                !- Sun Exposure
   NoWind,                !- Wind Exposure
   1,                 !- View Factor to Ground
   4,                 !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
   -13,                !- Vertex 1 X-coordinate {m}
   13,                !- Vertex 1 Y-coordinate {m}
   0,                 !- Vertex 1 Z-coordinate {m}
   -17.5,                 !- Vertex 2 X-coordinate {m}
   17.5,                 !- Vertex 2 Y-coordinate {m}
   0,                 !- Vertex 2 Z-coordinate {m}
   17.5,                 !- Vertex 3 X-coordinate {m}
   17.5,                 !- Vertex 3 Y-coordinate {m}
   0,                 !- Vertex 3 Z-coordinate {m}
   13,                !- Vertex 4 X-coordinate {m}
   13,                !- Vertex 4 Y-coordinate {m}
   0;                 !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
   zonename[]:CEILING,          !- User Supplied Surface Name
   ROOF,               !- Surface Type
   roof_const_type[],               !- Construction Name of the Surface
   zonename[],               !- InsideFaceEnvironment
   ExteriorEnvironment,              !- OutsideFaceEnvironment
   ,               !- OutsideFaceEnvironment Object
   SunExposed,                !- Sun Exposure
   WindExposed,                !- Wind Exposure
   0,                 !- View Factor to Ground
   4,                 !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
   -17.5,                 !- Vertex 1 X-coordinate {m}
   17.5,                 !- Vertex 1 Y-coordinate {m}
   ceilheight[],                 !- Vertex 1 Z-coordinate {m}
   -13,                !- Vertex 2 X-coordinate {m}
   13,                !- Vertex 2 Y-coordinate {m}
   ceilheight[],                 !- Vertex 2 Z-coordinate {m}
   13,                !- Vertex 3 X-coordinate {m}
   13,                !- Vertex 3 Y-coordinate {m}
```

```
    ceilheight[],                  !- Vertex 3 Z-coordinate {m}
    17.5,                  !- Vertex 4 X-coordinate {m}
    17.5,                  !- Vertex 4 Y-coordinate {m}
    ceilheight[];                  !- Vertex 4 Z-coordinate {m}

##enddef

##internalzone_GF.idf
!-Generator IDFEditor 1.13

!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-     Use '!' comments if they need to be retained when using the IDFEditor.

##def zone_I_GF[]
!-   ===========  ALL OBJECTS IN CLASS: ZONE ===========
!           zonename[]              name of zone
!           multiplier[]            multiplier
!           ceiheight[]             height of ceiling
!           IWALL-HL[]                          high level of internal wall
!           IWALL-LL[]                          low level of internal wall
!           CWALL-HL[]                          high level of core wall
!           CWALL-LL[]                          low level of core wall
!           int_wall_type[]                     Internal Wall Construction Type
!           window_glazing_type[]   Window Construction Type
!           floor_const_type[]      Typical Floor Construction Type
!           ceiling_const_type[]    Ceiling Construction Type
!           ground_const_type[]     Ground Construction Type
!           roof_const_type[]       Roof Construction Type
!           core_wall_type[]        Type of core wall

ZONE,
    GFSP_I,              !- Zone Name
    0,                   !- Relative North (to building) {deg}
    0,                   !- X Origin {m}
    0,                   !- Y Origin {m}
    0,                   !- Z Origin {m}
    1,                   !- Type
    1,                                          !- Multiplier
    ceilheight[],                  !- Ceiling Height {m}
    1200;                  !- Volume {m3}

!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER ===========

Surface:HeatTransfer,
    GFSP_I:IWALL-1,          !- User Supplied Surface Name
    WALL,                  !- Surface Type
    int_wall_type[],               !- Construction Name of the Surface
    GFSP_I,                !- InsideFaceEnvironment
    OtherZone,             !- OutsideFaceEnvironment
    GFSP_N:IWALL-2,          !- OutsideFaceEnvironment Object
    NoSun,                 !- Sun Exposure
    NoWind,                !- Wind Exposure
    0.5,                   !- View Factor to Ground
    4,                   !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
    13,                  !- Vertex 1 X-coordinate {m}
    13,                  !- Vertex 1 Y-coordinate {m}
    IWALL-HL[],                    !- Vertex 1 Z-coordinate {m}
    13,                  !- Vertex 2 X-coordinate {m}
    13,                  !- Vertex 2 Y-coordinate {m}
    IWALL-LL[],                    !- Vertex 2 Z-coordinate {m}
    -13,                   !- Vertex 3 X-coordinate {m}
    13,                  !- Vertex 3 Y-coordinate {m}
    IWALL-LL[],                    !- Vertex 3 Z-coordinate {m}
    -13,                   !- Vertex 4 X-coordinate {m}
    13,                  !- Vertex 4 Y-coordinate {m}
    IWALL-HL[];                    !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
    GFSP_I:IWALL-2,          !- User Supplied Surface Name
    WALL,                  !- Surface Type
    int_wall_type[],               !- Construction Name of the Surface
    GFSP_I,                !- InsideFaceEnvironment
    OtherZone,             !- OutsideFaceEnvironment
    GFSP_E:IWALL-2,          !- OutsideFaceEnvironment Object
    NoSun,                 !- Sun Exposure
```

```
  NoWind,              !- Wind Exposure
  0.5,                 !- View Factor to Ground
  4,                   !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  13,                  !- Vertex 1 X-coordinate {m}
  -13,                 !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],          !- Vertex 1 Z-coordinate {m}
  13,                  !- Vertex 2 X-coordinate {m}
  -13,                 !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],          !- Vertex 2 Z-coordinate {m}
  13,                  !- Vertex 3 X-coordinate {m}
  13,                  !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],          !- Vertex 3 Z-coordinate {m}
  13,                  !- Vertex 4 X-coordinate {m}
  13,                  !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];          !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:IWALL-3,      !- User Supplied Surface Name
  WALL,                !- Surface Type
  int_wall_type[],     !- Construction Name of the Surface
  GFSP_I,              !- InsideFaceEnvironment
  OtherZone,           !- OutsideFaceEnvironment
  GFSP_S:IWALL-2,      !- OutsideFaceEnvironment Object
  NoSun,               !- Sun Exposure
  NoWind,              !- Wind Exposure
  0.5,                 !- View Factor to Ground
  4,                   !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -13,                 !- Vertex 1 X-coordinate {m}
  -13,                 !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],          !- Vertex 1 Z-coordinate {m}
  -13,                 !- Vertex 2 X-coordinate {m}
  -13,                 !- Vertex 2 Y-coordinate {m}
 IWALL-LL[],           !- Vertex 2 Z-coordinate {m}
  13,                  !- Vertex 3 X-coordinate {m}
  -13,                 !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],          !- Vertex 3 Z-coordinate {m}
  13,                  !- Vertex 4 X-coordinate {m}
  -13,                 !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];          !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:IWALL-4,      !- User Supplied Surface Name
  WALL,                !- Surface Type
  int_wall_type[],     !- Construction Name of the Surface
  GFSP_I,              !- InsideFaceEnvironment
  OtherZone,           !- OutsideFaceEnvironment
  GFSP_W:IWALL-2,      !- OutsideFaceEnvironment Object
  NoSun,               !- Sun Exposure
  NoWind,              !- Wind Exposure
  0.5,                 !- View Factor to Ground
  4,                   !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -13,                 !- Vertex 1 X-coordinate {m}
  13,                  !- Vertex 1 Y-coordinate {m}
  IWALL-HL[],          !- Vertex 1 Z-coordinate {m}
  -13,                 !- Vertex 2 X-coordinate {m}
  13,                  !- Vertex 2 Y-coordinate {m}
  IWALL-LL[],          !- Vertex 2 Z-coordinate {m}
  -13,                 !- Vertex 3 X-coordinate {m}
  -13,                 !- Vertex 3 Y-coordinate {m}
  IWALL-LL[],          !- Vertex 3 Z-coordinate {m}
  -13,                 !- Vertex 4 X-coordinate {m}
  -13,                 !- Vertex 4 Y-coordinate {m}
  IWALL-HL[];          !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:CWALL-1,      !- User Supplied Surface Name
  WALL,                !- Surface Type
  core_wall_type[],    !- Construction Name of the Surface
  GFSP_I,              !- InsideFaceEnvironment
  OtherZone,           !- OutsideFaceEnvironment
  GFCORE:CWALL-1,      !- OutsideFaceEnvironment Object
  NoSun,               !- Sun Exposure
  NoWind,              !- Wind Exposure
  0.5,                 !- View Factor to Ground
  4,                   !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
```

```
  -7,                !- Vertex 1 X-coordinate {m}
  7,                 !- Vertex 1 Y-coordinate {m}
  CWALL-HL[],        !- Vertex 1 Z-coordinate {m}
  -7,                !- Vertex 2 X-coordinate {m}
  7,                 !- Vertex 2 Y-coordinate {m}
  CWALL-LL[],        !- Vertex 2 Z-coordinate {m}
  7,                 !- Vertex 3 X-coordinate {m}
  7,                 !- Vertex 3 Y-coordinate {m}
  CWALL-LL[],        !- Vertex 3 Z-coordinate {m}
  7,                 !- Vertex 4 X-coordinate {m}
  7,                 !- Vertex 4 Y-coordinate {m}
  CWALL-HL[];        !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:CWALL-2,    !- User Supplied Surface Name
  WALL,              !- Surface Type
  core_wall_type[],  !- Construction Name of the Surface
  GFSP_I,            !- InsideFaceEnvironment
  OtherZone,         !- OutsideFaceEnvironment
  GFCORE:CWALL-2,    !- OutsideFaceEnvironment Object
  NoSun,             !- Sun Exposure
  NoWind,            !- Wind Exposure
  0.5,               !- View Factor to Ground
  4,                 !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  7,                 !- Vertex 1 X-coordinate {m}
  7,                 !- Vertex 1 Y-coordinate {m}
  CWALL-HL[],        !- Vertex 1 Z-coordinate {m}
  7,                 !- Vertex 2 X-coordinate {m}
  7,                 !- Vertex 2 Y-coordinate {m}
  CWALL-LL[],        !- Vertex 2 Z-coordinate {m}
  7,                 !- Vertex 3 X-coordinate {m}
  -7,                !- Vertex 3 Y-coordinate {m}
  CWALL-LL[],        !- Vertex 3 Z-coordinate {m}
  7,                 !- Vertex 4 X-coordinate {m}
  -7,                !- Vertex 4 Y-coordinate {m}
  CWALL-HL[];        !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:CWALL-3,    !- User Supplied Surface Name
  WALL,              !- Surface Type
  core_wall_type[],  !- Construction Name of the Surface
  GFSP_I,            !- InsideFaceEnvironment
  OtherZone,         !- OutsideFaceEnvironment
  GFCORE:CWALL-3,    !- OutsideFaceEnvironment Object
  NoSun,             !- Sun Exposure
  NoWind,            !- Wind Exposure
  0.5,               !- View Factor to Ground
  4,                 !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  7,                 !- Vertex 1 X-coordinate {m}
  -7,                !- Vertex 1 Y-coordinate {m}
  CWALL-HL[],        !- Vertex 1 Z-coordinate {m}
  7,                 !- Vertex 2 X-coordinate {m}
  -7,                !- Vertex 2 Y-coordinate {m}
  CWALL-LL[],        !- Vertex 2 Z-coordinate {m}
  -7,                !- Vertex 3 X-coordinate {m}
  -7,                !- Vertex 3 Y-coordinate {m}
  CWALL-LL[],        !- Vertex 3 Z-coordinate {m}
  -7,                !- Vertex 4 X-coordinate {m}
  -7,                !- Vertex 4 Y-coordinate {m}
  CWALL-HL[];        !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:CWALL-4,    !- User Supplied Surface Name
  WALL,              !- Surface Type
  core_wall_type[],  !- Construction Name of the Surface
  GFSP_I,            !- InsideFaceEnvironment
  OtherZone,         !- OutsideFaceEnvironment
  GFCORE:CWALL-4,    !- OutsideFaceEnvironment Object
  NoSun,             !- Sun Exposure
  NoWind,            !- Wind Exposure
  0.5,               !- View Factor to Ground
  4,                 !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -7,                !- Vertex 1 X-coordinate {m}
  -7,                !- Vertex 1 Y-coordinate {m}
  CWALL-HL[],        !- Vertex 1 Z-coordinate {m}
```

```
  -7,                !- Vertex 2 X-coordinate {m}
  -7,                !- Vertex 2 Y-coordinate {m}
  CWALL-LL[],                !- Vertex 2 Z-coordinate {m}
  -7,                !- Vertex 3 X-coordinate {m}
  7,                !- Vertex 3 Y-coordinate {m}
  CWALL-LL[],                !- Vertex 3 Z-coordinate {m}
  -7,                !- Vertex 4 X-coordinate {m}
  7,                !- Vertex 4 Y-coordinate {m}
  CWALL-HL[];                !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:FLOOR-1,        !- User Supplied Surface Name
  FLOOR,                !- Surface Type
  ground_const_type[],              !- Construction Name of the Surface
  GFSP_I,                !- InsideFaceEnvironment
  Ground,                !- OutsideFaceEnvironment
  ,                !- OutsideFaceEnvironment Object
  NoSun,                !- Sun Exposure
  NoWind,                !- Wind Exposure
  1,                !- View Factor to Ground
  4,                !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -7,                !- Vertex 1 X-coordinate {m}
  7,                !- Vertex 1 Y-coordinate {m}
  0,                !- Vertex 1 Z-coordinate {m}
  -7,                !- Vertex 2 X-coordinate {m}
  13,                !- Vertex 2 Y-coordinate {m}
  0,                !- Vertex 2 Z-coordinate {m}
  7,                !- Vertex 3 X-coordinate {m}
  13,                !- Vertex 3 Y-coordinate {m}
  0,                !- Vertex 3 Z-coordinate {m}
  7,                !- Vertex 4 X-coordinate {m}
  7,                !- Vertex 4 Y-coordinate {m}
  0;                !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:FLOOR-2,        !- User Supplied Surface Name
  FLOOR,                !- Surface Type
  ground_const_type[],              !- Construction Name of the Surface
  GFSP_I,                !- InsideFaceEnvironment
  Ground,                !- OutsideFaceEnvironment
  ,                !- OutsideFaceEnvironment Object
  NoSun,                !- Sun Exposure
  NoWind,                !- Wind Exposure
  1,                !- View Factor to Ground
  4,                !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  7,                !- Vertex 1 X-coordinate {m}
  -13,                !- Vertex 1 Y-coordinate {m}
  0,                !- Vertex 1 Z-coordinate {m}
  7,                !- Vertex 2 X-coordinate {m}
  13,                !- Vertex 2 Y-coordinate {m}
  0,                !- Vertex 2 Z-coordinate {m}
  13,                !- Vertex 3 X-coordinate {m}
  13,                !- Vertex 3 Y-coordinate {m}
  0,                !- Vertex 3 Z-coordinate {m}
  13,                !- Vertex 4 X-coordinate {m}
  -13,                !- Vertex 4 Y-coordinate {m}
  0;                !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:FLOOR-3,        !- User Supplied Surface Name
  FLOOR,                !- Surface Type
  ground_const_type[],              !- Construction Name of the Surface
  GFSP_I,                !- InsideFaceEnvironment
  Ground,                !- OutsideFaceEnvironment
  ,                !- OutsideFaceEnvironment Object
  NoSun,                !- Sun Exposure
  NoWind,                !- Wind Exposure
  1,                !- View Factor to Ground
  4,                !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -7,                !- Vertex 1 X-coordinate {m}
  -13,                !- Vertex 1 Y-coordinate {m}
  0,                !- Vertex 1 Z-coordinate {m}
  -7,                !- Vertex 2 X-coordinate {m}
  -7,                !- Vertex 2 Y-coordinate {m}
  0,                !- Vertex 2 Z-coordinate {m}
```

```
  7,               !- Vertex 3 X-coordinate {m}
  -7,              !- Vertex 3 Y-coordinate {m}
  0,               !- Vertex 3 Z-coordinate {m}
  7,               !- Vertex 4 X-coordinate {m}
  -13,             !- Vertex 4 Y-coordinate {m}
  0;               !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:FLOOR-4,        !- User Supplied Surface Name
  FLOOR,                 !- Surface Type
  ground_const_type[],   !- Construction Name of the Surface
  GFSP_I,                !- InsideFaceEnvironment
  Ground,                !- OutsideFaceEnvironment
  ,                      !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  1,                     !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -13,             !- Vertex 1 X-coordinate {m}
  -13,             !- Vertex 1 Y-coordinate {m}
  0,               !- Vertex 1 Z-coordinate {m}
  -13,             !- Vertex 2 X-coordinate {m}
  13,              !- Vertex 2 Y-coordinate {m}
  0,               !- Vertex 2 Z-coordinate {m}
  -7,              !- Vertex 3 X-coordinate {m}
  13,              !- Vertex 3 Y-coordinate {m}
  0,               !- Vertex 3 Z-coordinate {m}
  -7,              !- Vertex 4 X-coordinate {m}
  -13,             !- Vertex 4 Y-coordinate {m}
  0;               !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:CEILING-1,      !- User Supplied Surface Name
  CEILING,               !- Surface Type
  ceiling_const_type[],  !- Construction Name of the Surface
  GFSP_I,                !- InsideFaceEnvironment
  OtherZone,             !- OutsideFaceEnvironment
  GFSP_I:CEILING-1,      !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0,                     !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  -7,              !- Vertex 1 X-coordinate {m}
  13,              !- Vertex 1 Y-coordinate {m}
  ceilheight[],    !- Vertex 1 Z-coordinate {m}
  -7,              !- Vertex 2 X-coordinate {m}
  7,               !- Vertex 2 Y-coordinate {m}
  ceilheight[],    !- Vertex 2 Z-coordinate {m}
  7,               !- Vertex 3 X-coordinate {m}
  7,               !- Vertex 3 Y-coordinate {m}
  ceilheight[],    !- Vertex 3 Z-coordinate {m}
  7,               !- Vertex 4 X-coordinate {m}
  13,              !- Vertex 4 Y-coordinate {m}
  ceilheight[];    !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
  GFSP_I:CEILING-2,      !- User Supplied Surface Name
  CEILING,               !- Surface Type
  ceiling_const_type[],  !- Construction Name of the Surface
  GFSP_I,                !- InsideFaceEnvironment
  OtherZone,             !- OutsideFaceEnvironment
  GFSP_I:CEILING-2,      !- OutsideFaceEnvironment Object
  NoSun,                 !- Sun Exposure
  NoWind,                !- Wind Exposure
  0,                     !- View Factor to Ground
  4,                     !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
  7,               !- Vertex 1 X-coordinate {m}
  13,              !- Vertex 1 Y-coordinate {m}
  ceilheight[],    !- Vertex 1 Z-coordinate {m}
  7,               !- Vertex 2 X-coordinate {m}
  -13,             !- Vertex 2 Y-coordinate {m}
  ceilheight[],    !- Vertex 2 Z-coordinate {m}
  13,              !- Vertex 3 X-coordinate {m}
  -13,             !- Vertex 3 Y-coordinate {m}
  ceilheight[],    !- Vertex 3 Z-coordinate {m}
```

```
   13,                 !- Vertex 4 X-coordinate {m}
   13,                 !- Vertex 4 Y-coordinate {m}
   ceilheight[];                  !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
   GFSP_I:CEILING-3,       !- User Supplied Surface Name
   CEILING,              !- Surface Type
   ceiling_const_type[],              !- Construction Name of the Surface
   GFSP_I,               !- InsideFaceEnvironment
   OtherZone,            !- OutsideFaceEnvironment
   GFSP_I:CEILING-3,         !- OutsideFaceEnvironment Object
   NoSun,                !- Sun Exposure
   NoWind,               !- Wind Exposure
   0,                    !- View Factor to Ground
   4,                    !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
   -7,                 !- Vertex 1 X-coordinate {m}
   -7,                 !- Vertex 1 Y-coordinate {m}
   ceilheight[],                 !- Vertex 1 Z-coordinate {m}
   -7,                 !- Vertex 2 X-coordinate {m}
   -13,                  !- Vertex 2 Y-coordinate {m}
   ceilheight[],                  !- Vertex 2 Z-coordinate {m}
   7,                 !- Vertex 3 X-coordinate {m}
   -13,                  !- Vertex 3 Y-coordinate {m}
   ceilheight[],                  !- Vertex 3 Z-coordinate {m}
   7,                 !- Vertex 4 X-coordinate {m}
   -7,                 !- Vertex 4 Y-coordinate {m}
   ceilheight[];                  !- Vertex 4 Z-coordinate {m}

Surface:HeatTransfer,
   GFSP_I:CEILING-4,       !- User Supplied Surface Name
   CEILING,              !- Surface Type
   ceiling_const_type[],              !- Construction Name of the Surface
   GFSP_I,               !- InsideFaceEnvironment
   OtherZone,            !- OutsideFaceEnvironment
   GFSP_I:CEILING-4,         !- OutsideFaceEnvironment Object
   NoSun,                !- Sun Exposure
   NoWind,               !- Wind Exposure
   0,                    !- View Factor to Ground
   4,                    !- Number of Surface Vertice Groups -- Number of (X,Y,Z) groups in this surface
   -13,                  !- Vertex 1 X-coordinate {m}
   13,                 !- Vertex 1 Y-coordinate {m}
   ceilheight[],                  !- Vertex 1 Z-coordinate {m}
   -13,                  !- Vertex 2 X-coordinate {m}
   -13,                  !- Vertex 2 Y-coordinate {m}
   ceilheight[],                  !- Vertex 2 Z-coordinate {m}
   -7,                 !- Vertex 3 X-coordinate {m}
   -13,                  !- Vertex 3 Y-coordinate {m}
   ceilheight[],                  !- Vertex 3 Z-coordinate {m}
   -7,                 !- Vertex 4 X-coordinate {m}
   13,                 !- Vertex 4 Y-coordinate {m}
   ceilheight[];                  !- Vertex 4 Z-coordinate {m}

##enddef

##include activities_sch.idf
!-Generator IDFEditor 1.13
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-     Use '!' comments if they need to be retained when using the IDFEditor.

!-   ===============ALL OBJECTS IN CLASS: SCHEDULE:COMPACT =====================

 Schedule:Compact ,
 always On,                     !-Name
 Fraction,                       !-Schedule Type
 Through: 12/31,                !-Complex Field #1
 For: AllDays,                   !-Complex Field #2
 Until: 24:00,                    !-Complex Field #3
 1.0;                              !-Complex Field #4

 Schedule:Compact,
 PVEfficiency,                  !-Name
 Fraction,                       !-ScheduleType
 Through: 12/31,              !-Complex Field #1
 For: AllDays,                 !-Complex Field #2
 Until: 24:00,                  !-Complex Field #3
```

```
 0.12;                           !-Complex Field #4

##include construction_material.idf
!-Generator IDFEditor 1.13
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-     Use '!' comments if they need to be retained when using the IDFEditor.

!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:REGULAR ===========

MATERIAL:REGULAR,
    BUILDUP,                 !- Name
    VeryRough,               !- Roughness
    0.0095,                  !- Thickness {m}
    0.162,                   !- Conductivity {W/m-K}
    1121,                    !- Density {kg/m3}
    1464,                    !- Specific Heat {J/kg-K}
    0.9,                     !- Absorptance:Thermal
    0.7,                     !- Absorptance:Solar
    0.7;                     !- Absorptance:Visible

MATERIAL:REGULAR,
    FCPANEL,                 !- Name
    MediumSmooth,            !- Roughness
    0.0191,                  !- Thickness {m}
    0.057,                   !- Conductivity {W/m-K}
    288,                     !- Density {kg/m3}
    1339,                    !- Specific Heat {J/kg-K}
    0.9,                     !- Absorptance:Thermal
    0.7,                     !- Absorptance:Solar
    0.7;                     !- Absorptance:Visible

MATERIAL:REGULAR,
    GYPBORD,                 !- Name
    MediumSmooth,            !- Roughness
    0.0159,                  !- Thickness {m}
    0.1602,                  !- Conductivity {W/m-K}
    801,                     !- Density {kg/m3}
    837,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Absorptance:Thermal
    0.75,                    !- Absorptance:Solar
    0.75;                    !- Absorptance:Visible

MATERIAL:REGULAR,
    HWCONC,                  !- Name
    MediumRough,             !- Roughness
    0.2032,                  !- Thickness {m}
    1.31,                    !- Conductivity {W/m-K}
    2243,                    !- Density {kg/m3}
    837,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Absorptance:Thermal
    0.72,                    !- Absorptance:Solar
    0.72;                    !- Absorptance:Visible

MATERIAL:REGULAR,
    LWCONC-1,                !- Name
    MediumRough,             !- Roughness
    0.1524,                  !- Thickness {m}
    0.3603,                  !- Conductivity {W/m-K}
    1281,                    !- Density {kg/m3}
    837,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Absorptance:Thermal
    0.65,                    !- Absorptance:Solar
    0.65;                    !- Absorptance:Visible

MATERIAL:REGULAR,
    LWCONC-2,                !- Name
    MediumRough,             !- Roughness
    0.0762,                  !- Thickness {m}
    0.3603,                  !- Conductivity {W/m-K}
    1281,                    !- Density {kg/m3}
    837,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Absorptance:Thermal
    0.65,                    !- Absorptance:Solar
    0.65;                    !- Absorptance:Visible
```

```
MATERIAL:REGULAR,
  MOSAIC,            !- Name
  MediumRough,       !- Roughness
  0.005,             !- Thickness {m}
  1.8016,            !- Conductivity {W/m-K}
  2243,              !- Density {kg/m3}
  335,               !- Specific Heat {J/kg-K}
  0.9,               !- Absorptance:Thermal
  0.65,              !- Absorptance:Solar
  0.65;              !- Absorptance:Visible

MATERIAL:REGULAR,
  MOTAR,             !- Name
  MediumRough,       !- Roughness
  0.0191,            !- Thickness {m}
  0.7207,            !- Conductivity {W/m-K}
  1858,              !- Density {kg/m3}
  837,               !- Specific Heat {J/kg-K}
  0.9,               !- Absorptance:Thermal
  0.54,              !- Absorptance:Solar
  0.54;              !- Absorptance:Visible

MATERIAL:REGULAR,
  PLASTER,           !- Name
  Smooth,            !- Roughness
  0.0191,            !- Thickness {m}
  0.23,              !- Conductivity {W/m-K}
  721,               !- Density {kg/m3}
  837,               !- Specific Heat {J/kg-K}
  0.9,               !- Absorptance:Thermal
  0.78,              !- Absorptance:Solar
  0.78;              !- Absorptance:Visible

MATERIAL:REGULAR,
  PLYWOOD,           !- Name
  MediumSmooth,      !- Roughness
  0.0191,            !- Thickness {m}
  0.1154,            !- Conductivity {W/m-K}
  545,               !- Density {kg/m3}
  1213,              !- Specific Heat {J/kg-K}
  0.9,               !- Absorptance:Thermal
  0.78,              !- Absorptance:Solar
  0.78;              !- Absorptance:Visible

MATERIAL:REGULAR,
  RFINSUL,           !- Name
  Rough,             !- Roughness
  0.0508,            !- Thickness {m}
  0.052,             !- Conductivity {W/m-K}
  256,               !- Density {kg/m3}
  837,               !- Specific Heat {J/kg-K}
  0.9,               !- Absorptance:Thermal
  0.75,              !- Absorptance:Solar
  0.75;              !- Absorptance:Visible

MATERIAL:REGULAR,
  SCREED,            !- Name
  MediumRough,       !- Roughness
  0.0508,            !- Thickness {m}
  0.36,              !- Conductivity {W/m-K}
  1281,              !- Density {kg/m3}
  837,               !- Specific Heat {J/kg-K}
  0.9,               !- Absorptance:Thermal
  0.65,              !- Absorptance:Solar
  0.65;              !- Absorptance:Visible

MATERIAL:REGULAR,
  SLAG,              !- Name
  Rough,             !- Roughness
  0.0127,            !- Thickness {m}
  1.442,             !- Conductivity {W/m-K}
  881,               !- Density {kg/m3}
  1674,              !- Specific Heat {J/kg-K}
  0.9,               !- Absorptance:Thermal
  0.65,              !- Absorptance:Solar
```

```
  0.65;                !- Absorptance:Visible


 !-   ===========  ALL OBJECTS IN CLASS: MATERIAL:AIR ===========

 MATERIAL:AIR,
    AIRGAP,              !- Name
    0.149;               !- Thermal Resistance {m2-K/W}

 MATERIAL:AIR,
    AIRVOID,             !- Name
    0.16;                !- Thermal Resistance {m2-K/W}


!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:REGULAR-R ===========

MATERIAL:REGULAR-R,
   CARPET,              !- Name
   Rough,               !- Roughness
   0.367,               !- Thermal Resistance {m2-K/W}
   0.9,                 !- Absorptance:Thermal
   0.75,                !- Absorptance:Solar
   0.75;                !- Absorptance:Visible

MATERIAL:REGULAR-R,
   GLASS,               !- Name
   VerySmooth,          !- Roughness
   0.0057,              !- Thermal Resistance {m2-K/W}
   0.9,                 !- Absorptance:Thermal
   0.7,                 !- Absorptance:Solar
   0.7;                 !- Absorptance:Visible

MATERIAL:REGULAR-R,
   WALLPAPER,           !- Name
   Rough,               !- Roughness
   0.0106,              !- Thermal Resistance {m2-K/W}
   0.9,                 !- Absorptance:Thermal
   0.75,                !- Absorptance:Solar
   0.75;                !- Absorptance:Visible


!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========

 CONSTRUCTION,
   WALL-1,                       !-Name
   GLASS,                        !-Outside Layer
   AIRGAP,                       !-Layer#2
   HWCONC,                       !-Layer#3
   WALLPAPER;                    !-Layer#4


 CONSTRUCTION,
   RF,                  !- Name
   SLAG,                !- Outside Layer
   BUILDUP,             !- Layer #2
   RFINSUL,             !- Layer #3
   HWCONC,              !- Layer #4
   AIRVOID,             !- Layer #5
   FCPANEL;             !- Layer #6

CONSTRUCTION,
   GND-FLR,             !- Name
   HWCONC,              !- Outside Layer
   SCREED,              !- Layer #2
   CARPET;              !- Layer #3

CONSTRUCTION,
   FLOOR,               !- Name
   FCPANEL,             !- Outside Layer
   AIRVOID,             !- Layer #2
   LWCONC-1,            !- Layer #3
   SCREED,              !- Layer #4
   CARPET;              !- Layer #5

CONSTRUCTION,
```

```
   CEILING,              !- Name
   CARPET,               !- Outside Layer
   SCREED,               !- Layer #2
   LWCONC-1,             !- Layer #3
   AIRVOID,              !- Layer #4
   FCPANEL;              !- Layer #5

CONSTRUCTION,
   INT-PART,             !- Name
   GYPBORD,              !- Outside Layer
   AIRGAP,               !- Layer #2
   GYPBORD;              !- Layer #3

CONSTRUCTION,
   COREWALL,             !- Name
   MOSAIC,               !- Outside Layer
   MOTAR,                !- Layer #2
   HWCONC,               !- Layer #3
   PLASTER,              !- Layer #4
   WALLPAPER;            !- Layer #5

CONSTRUCTION,
   RE-GLASS with no shade,  !- Name
   GLAZ-1;               !- Outside Layer

CONSTRUCTION,
   RE-GLASS with interior shade,  !- Name
   GLAZ-1,               !- Outside Layer
   Curtain - medium reflect and medium trans;  !- Layer #2

CONSTRUCTION,
   COREFLOOR,            !- Name
   LWCONC-1,             !- Outside Layer
   SCREED;               !- Layer #2

CONSTRUCTION,
   CORECEIL,             !- Name
   SCREED,               !- Outside Layer
   LWCONC-1;             !- Layer #2

CONSTRUCTION,
   CORERF,               !- Name
   SLAG,                 !- Outside Layer
   BUILDUP,              !- Layer #2
   RFINSUL,              !- Layer #3
   HWCONC;               !- Layer #4


##include glazing_material.idf
!-Generator IDFEditor 1.13
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-     Use '!' comments if they need to be retained when using the IDFEditor.

!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:WINDOWGLASS ===========

MATERIAL:WINDOWGLASS,
   GLAZ-1,               !- Name
   SpectralAverage,      !- Optical Data Type
   ,                     !- Name of Window Glass Spectral Data Set
   0.006,                !- Thickness {m}
   0.2,                  !- Solar Transmittance at Normal Incidence
   0.16,                 !- Solar Reflectance at Normal Incidence: Front Side
   0.39,                 !- Solar Reflectance at Normal Incidence: Back Side
   0.3,                  !- Visible Transmittance at Normal Incidence
   0.16,                 !- Visible Reflectance at Normal Incidence: Front Side
   0.29,                 !- Visible Reflectance at Normal Incidence: Back Side
   0,                    !- IR Transmittance at Normal Incidence
   0.84,                 !- IR Hemispherical Emissivity: Front Side
   0.60,                 !- IR Hemispherical Emissivity: Back Side
   0.9;                  !- Conductivity {W/m-K}

!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:WINDOWSHADE ===========

MATERIAL:WINDOWSHADE,
   Curtain - medium reflect and medium trans,  !- Name
```

```
  0.25,              !- Solar transmittance
  0.5,               !- Solar Reflectance
  0.4,               !- Visible transmittance
  0.5,               !- Visible reflectance
  0.9,               !- Thermal hemispherical emissivity
  0.0,               !- Thermal transmittance
  0.005,             !- Thickness {m}
  0.1,               !- Conductivity {W/m-K}
  0.05,              !- Shade-to-glass distance {m}
  0.5,               !- Top opening multiplier
  0.5,               !- Bottom opening multiplier
  0.5,               !- Left-side opening multiplier
  0.5,               !- Right-side opening multiplier
  0.0;               !- Air flow permeability


##include blindcontrol.idf
!-Generator IDFEditor 1.13
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-    Use '!' comments if they need to be retained when using the IDFEditor.


!-   =========== ALL OBJECTS IN CLASS: WINDOWSHADINGCONTROL ===========
##def window_shading_control[]
WindowShadingControl,
  shading_name[],              !- User Supplied Shading Control Name
  InteriorShade,         !- Shading Type
  shading_construcion[],   !- Name of construction with shading
  OnIfHighSolarOnWindow,   !- Shading Control Type
  ,                    !- Schedule Name
  solar_setpoint_value[],  !- SetPoint {W/m2, W or deg C}
  NO,                  !- Shading Control Is Scheduled
  Shading_glare_control[], !- Glare Control Is Active
  ,                    !- Material Name of Shading Device
  ,                    !- Type of Slat Angle Control for Blinds
  ;                    !- Slat Angle Schedule Name

##enddef


##include daylightdetail.idf
!-Generator IDFEditor 1.13
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-    Use '!' comments if they need to be retained when using the IDFEditor.

##def p_zone[]

!-   =========== ALL OBJECTS IN CLASS: DAYLIGHTING:DETAILED =========
! zonename[]          Name of zone
! x-coord[]          x-coordinate of first reference point {m}
! y-coord[]          y-coordinate of first reference point {m}
! z-coord[]          z-coordinate of first reference point {m}
! azi_ang[]          azimuth angle of view direction relative to window for glare calculation {deg}
! refpt1ill[]   Illuminance setpoint at first reference point {lux}
! glare_index[]                    The Maximum allowable discomfort glare {DGI}
! min_power_input[]       The minimum power consumed by lighting {fraction}
! min_lgt_output[]        The minimum light can be output {fraction}

DAYLIGHTING:DETAILED,
  zonename[],                       !- Zone name
  1,                                !- Total Daylighting reference points
  x-coord[],              !- X-coordinate of first reference point {m}
  y-coord[],              !- Y-coordinate of first reference point {m}
  z-coord[],              !- Z-coordinate of first reference point {m}
  0.0,                    !- X-coordinate of second reference point {m}
  0.0,                    !- Y-coordinate of second reference point {m}
  0.0,                    !- Z-coordinate of second reference point {m}
  1,                                !- Fraction of zone controlled by first reference point
  0,                                !- Fraction of zone controlled by second reference point
  refpt1ill[], !- Illuminance setpoint at first reference point
  0,                      !- Illuminance setpoint at second reference point
  1,          !- Lighting control type {1=continuous, 2=stepped, 3=continuous/off}
  azi_ang[],              !- Azimuth angle of view direction relative to window for glare calculation {deg}
  glare_index[],          !- Maxim allowable discomfort glare index
  min_power_input[],      !- Minimum input power fraction for continuous dimming control
```

```
  min_lgt_output[],         !- minimum light output fraction for continuous dimming control
  0,                        !- Number of steps, excluding off, for stepped control
  1;                        !- Probability electric lighting will be reset when needed {used only for stepped control}

##enddef

##include VAV_heating.idf
!***********************************************************************
!         This is a basic description for a VAV system with reheat and
!         control by a dual deadband. It is a five zone VAV boxes and
!         a draw through system.
!
!         List of variables:
!
!                  systemname          The name of system (usually the
!                                               floor number)
!                  zone1                        The 1st zone for a VAV system
!                  zone2                        The 2nd zone for a VAV system
!                  zone3                        The 3rd zone for a VAV system
!                  zone4                        The 4th zone for a VAV system
!                  zone5                        The 5th zone for a VAV system
!                  fan_eff                      Overall Fan Efficiency {fraction}
!                  fan_delta_press              Fan Delta Pressure {Pa}
!                  fan_motor_eff                Fan motor efficiency {fraction}
!                  maxairflowrate               System maximum supply flowrate
!                                               {m3/s}
!                  minairflowrate               System minimum supply flowrate
!                                               {m3/s}
!                  CHW_flowrate                 System chilled water flowrate
!                                               for cooling coil {m3/s}
!                  maxOA                        Maximum outdoor air flowrate
!                                               {m3/s}
!                  minOA                        Minimum outdoor air flowrate
!                                               {m3/s}
!                  zone1airflowrate    Supply air flowrate for 1st
!                                               zone {m3/s}
!                  zone2airflowrate    Supply air flowrate for 2nd
!                                               zone {m3/s}
!                  zone3airflowrate    Supply air flowrate for 3rd
!                                               zone {m3/s}
!                  zone4airflowrate    Supply air flowrate for 4th
!                                               zone {m3/s}
!                  zone5airflowrate    Supply air flowrate for 5th
!                                               zone {m3/s}
!                  zone1reheatcoilcap  Reheat coil capacity for
!                                               the 1st zone (W)
!                  zone2reheatcoilcap  Reheat coil capacity for
!                                               the 2nd zone (W)
!                  zone3reheatcoilcap  Reheat coil capacity for
!                                               the 3rd zone (W)
!                  zone4reheatcoilcap  Reheat coil capacity for
!                                               the 4th zone (W)
!                  zone5reheatcoilcap  Reheat coil capacity for
!                                               the 5thzone (W)
!***************************************************************************

##def Vav_c_nh[]

!-   ===========  ALL OBJECTS IN CLASS: NODE LIST ===========

NODE LIST,
  systemname[] supply air temp nodes,!- Node List Name
  systemname[] Air Loop outlet node; !- Node_ID_1

NODE LIST,
  systemname[] OutsideAirInletNode,  !- Node List Name
  systemname[] OA Inlet Node;        !- Node_ID_1

NODE LIST,
  systemname[] Supply Fan Upstream Nodes,  !- Node List Name
  systemname[]  Mixed Air Node,       !- Node_ID_1
  systemname[]  Cooling Coil Air Outlet Node;  !- Node_ID_2

NODE LIST,
  zone1[] Inlets,           !- Node List Name
```

```
    zone1[] Reheat air outlet node;  !- Node_ID_1

NODE LIST,
    zone2[] Inlets,           !- Node List Name
    zone2[] Reheat air outlet node;  !- Node_ID_1

NODE LIST,
    zone3[] Inlets,           !- Node List Name
    zone3[] Reheat air outlet node;  !- Node_ID_1

NODE LIST,
    zone4[] Inlets,           !- Node List Name
    zone4[] Reheat air outlet node;  !- Node_ID_1

NODE LIST,
    zone5[] Inlets,           !- Node List Name
    zone5[] Reheat air outlet node;  !- Node_ID_1

!-   ===========  ALL OBJECTS IN CLASS: OUTSIDE AIR INLET NODE LIST ===========

OUTSIDE AIR INLET NODE LIST,
    systemname[] OutsideAirInletNode;  !- 1st Node name or node list name

!-   ===========  ALL OBJECTS IN CLASS: BRANCH LIST ===========

BRANCH LIST,
    systemname[] air Loop Branches,    !- Branch List Name
    systemname[] Air Loop Main Branch; !- Branch Name 1

!-   ===========  ALL OBJECTS IN CLASS: BRANCH ===========

BRANCH,
    systemname[] Air Loop Main Branch,  !- Branch Name
    maxairflowrate[],                 !- Maximum Branch Flow Rate {m3/s}
    Outside Air System,      !- Comp1 Type
    systemname[] OA Sys,              !- Comp1 Name
    systemname[] Air Loop Inlet Node,  !- Comp1 Inlet Node Name
    systemname[] Mixed air node,       !- Comp1 Outlet Node Name
    PASSIVE,                 !- Comp1 Branch Control Type
    Coil:Water:Cooling,      !- Comp2 Type
    systemname[] Cooling Coil,         !- Comp2 Name
    systemname[] Mixed air node,       !- Comp2 Inlet Node Name
    systemname[] Cooling Coil air outlet node,  !- Comp2 Outlet Node Name
    PASSIVE,                 !- Comp2 Branch Control Type
    Fan:simple:variablevolume,  !- Comp3 Type
    systemname[] Supply Fan,           !- Comp3 Name
    systemname[] Cooling Coil air outlet node,  !- Comp3 Inlet Node Name
    systemname[] air loop outlet node, !- Comp3 Outlet Node Name
    ACTIVE;                  !- Comp3 Branch Control Type

!-   ===========  ALL OBJECTS IN CLASS: AIR PRIMARY LOOP ===========

AIR PRIMARY LOOP,
    systemname[] air Loop System,      !- Primary Air Loop Name
    systemname[] System controllers,   !- Name: Controller List
    Reheat System Avail List,!- Name: System Availability Manager List
    maxairflowrate[],                 !- Primary air design volumetric flow rate {m3/s}
    systemname[] air Loop Branches,    !- Air Loop Branch List Name
    ,                        !- Air Loop Connector List Name
    systemname[] air loop inlet node,  !- ReturnAir AirLoop Inlet Node
    systemname[] Return air mixer outlet node,  !- ZoneEquipGroup Outlet Node
    systemname[] zone equip inlet node,!- SupplyAirPath ZoneEquipGroup Inlet Nodes
   systemname[] air loop outlet node; !- AirLoop Outlet Nodes

!-   ===========  ALL OBJECTS IN CLASS: CONTROLLER LIST ===========

CONTROLLER LIST,
    systemname[] System controllers,   !- Name
    CONTROLLER:SIMPLE,       !- Controller Type 1
    systemname[] Cooling Coil Controller;  !- Controller Name 1

CONTROLLER LIST,
    systemname[] OA sys controllers,   !- Name
    CONTROLLER:OUTSIDE AIR,  !- Controller Type 1
    systemname[] OA controller;        !- Controller Name 1
```

```
!-   ===========  ALL OBJECTS IN CLASS: AIR LOOP EQUIPMENT LIST ===========

AIR LOOP EQUIPMENT LIST,
    systemname[] OA SYS Equip,         !- Name
    Outside air mixer,       !- KEY--System Component 1
    systemname[] OA Mixing Box;        !- Component Name 1

!-   ===========  ALL OBJECTS IN CLASS: OUTSIDE AIR SYSTEM ===========

OUTSIDE AIR SYSTEM,
    systemname[] OA SYS,             !- Name
    systemname[] OA sys controllers,   !- Name: Controller List
    systemname[] OA SYS Equip,         !- Name of an Air Loop Equipment List
    Reheat System Avail List;!- Name of a System Availability Manager List

!-   ===========  ALL OBJECTS IN CLASS: OUTSIDE AIR MIXER ===========

OUTSIDE AIR MIXER,
    systemname[] OA Mixing Box,        !- Name
    systemname[] Mixed Air Node,       !- Mixed_Air_Node
    systemname[] OA Inlet Node,        !- Outside_Air_Stream_Node
    systemname[] Relief air outlet node,  !- Relief_Air_Stream_Node
    systemname[] Air Loop Inlet Node;  !- Return_Air_Stream_Node

!-   ===========  ALL OBJECTS IN CLASS: SET POINT MANAGER:SCHEDULED ===========

SET POINT MANAGER:SCHEDULED,
    systemname[] Supply air temp manager,  !- Name
    TEMP,                   !- Control variable
    supplytempsch[],  !- Schedule Name
    systemname[] supply air temp nodes;!- Name of the set point Node or Node List

SET POINT MANAGER:MIXED AIR,
    systemname[] Mixed air Temp Manager,  !- Name
    TEMP,                   !- Control variable:
    systemname[] Air Loop Outlet Node, !- reference set point node name
    systemname[] cooling coil Air outlet node,  !- fan inlet node name
    systemname[] Air Loop Outlet Node, !- fan outlet node name
    systemname[] Mixed air node;       !- Name of the set point Node or Node List

!-   ===========  ALL OBJECTS IN CLASS: CONTROLLER:SIMPLE ===========

CONTROLLER:SIMPLE,
    systemname[] Cooling Coil Controller,  !- Name
    TEMP,                   !- Control variable
    REVERSE,                !- Action
    FLOW,                   !- Actuator variable
    systemname[] air loop outlet node, !- Control_Node
    systemname[] Cooling coil water inlet node,  !- Actuator_Node
    0.002,                  !- Controller Convergence Tolerance: delta temp from setpoint temp {deltaC}
    CHW_flowrate[],              !- Max Actuated Flow {m3/s}
    0;                      !- Min Actuated Flow {m3/s}

!-   ===========  ALL OBJECTS IN CLASS: CONTROLLER:OUTSIDE AIR ===========
CONTROLLER:OUTSIDE AIR,
    systemname[] OA controller,        !- Name
    NO ECONOMIZER,           !- EconomizerChoice
    NO RETURN AIR TEMP LIMIT,!- ReturnAirTempLimit
    NO RETURN AIR ENTHALPY LIMIT,  !- ReturnAirEnthalpyLimit
    NO LOCKOUT,             !- Lockout
    FIXED MINIMUM,           !- MinimumLimit
    systemname[] Mixed Air Node,       !- Control_Node
    systemname[] OA Inlet Node,        !- Actuated_Node
    minOA[],                 !- minimum outside air flow rate {m3/s}
    maxOA[],                 !- maximum outside air flow rate {m3/s}
    19,                     !- temperature limit {C}
    4,                      !- temperature lower limit {C}
    ,                       !- enthalpy limit {J/kg}
    systemname[] Relief air outlet node,  !- Relief_Air_Outlet_Node
    systemname[] Air Loop Inlet Node,  !- Return_Air_Node
    Min OA Sch;             !- Minimum Outside Air Schedule Name

!-   ===========  ALL OBJECTS IN CLASS: CONTROLLED ZONE EQUIP CONFIGURATION ===========
```

```
CONTROLLED ZONE EQUIP CONFIGURATION,
   zone1[],               !- Zone Name
   zone1[] Zone Equipment,   !- List Name: Zone Equipment
   zone1[] Inlets,          !- Node List or Node Name: Zone Air Inlet Node(s)
   ,                     !- Node List or Node Name: Zone Air Exhaust Node(s)
   zone1[] node,           !- Zone Air Node Name
   zone1[] outlet node;      !- Zone Return Air Node Name

CONTROLLED ZONE EQUIP CONFIGURATION,
   zone2[],               !- Zone Name
   zone2[] Zone Equipment,   !- List Name: Zone Equipment
   zone2[] Inlets,          !- Node List or Node Name: Zone Air Inlet Node(s)
   ,                     !- Node List or Node Name: Zone Air Exhaust Node(s)
   zone2[] node,           !- Zone Air Node Name
   zone2[] outlet node;      !- Zone Return Air Node Name

CONTROLLED ZONE EQUIP CONFIGURATION,
   zone3[],               !- Zone Name
   zone3[] Zone Equipment,   !- List Name: Zone Equipment
   zone3[] Inlets,          !- Node List or Node Name: Zone Air Inlet Node(s)
   ,                     !- Node List or Node Name: Zone Air Exhaust Node(s)
   zone3[] node,           !- Zone Air Node Name
   zone3[] outlet node;      !- Zone Return Air Node Name

CONTROLLED ZONE EQUIP CONFIGURATION,
   zone4[],               !- Zone Name
   zone4[] Zone Equipment,   !- List Name: Zone Equipment
   zone4[] Inlets,          !- Node List or Node Name: Zone Air Inlet Node(s)
   ,                     !- Node List or Node Name: Zone Air Exhaust Node(s)
   zone4[] node,           !- Zone Air Node Name
   zone4[] outlet node;      !- Zone Return Air Node Name

CONTROLLED ZONE EQUIP CONFIGURATION,
   zone5[],               !- Zone Name
   zone5[] Zone Equipment,   !- List Name: Zone Equipment
   zone5[] Inlets,          !- Node List or Node Name: Zone Air Inlet Node(s)
   ,                     !- Node List or Node Name: Zone Air Exhaust Node(s)
   zone5[] node,           !- Zone Air Node Name
   zone5[] outlet node;      !- Zone Return Air Node Name

!-   ===========  ALL OBJECTS IN CLASS: ZONE EQUIPMENT LIST ===========

ZONE EQUIPMENT LIST,
   zone1[] Zone Equipment,   !- Name
   AIR DISTRIBUTION UNIT,   !- KEY--Zone Equipment Type 1
   zone1[] Term Reheat,      !- Type Name 1
   1,                    !- Cooling Priority
   1;                    !- Heating Priority

ZONE EQUIPMENT LIST,
   zone2[] Zone Equipment,   !- Name
   AIR DISTRIBUTION UNIT,   !- KEY--Zone Equipment Type 1
   zone2[] Term Reheat,      !- Type Name 1
   1,                    !- Cooling Priority
   1;                    !- Heating Priority

ZONE EQUIPMENT LIST,
   zone3[] Zone Equipment,   !- Name
   AIR DISTRIBUTION UNIT,   !- KEY--Zone Equipment Type 1
   zone3[] Term Reheat,      !- Type Name 1
   1,                    !- Cooling Priority
   1;                    !- Heating Priority

ZONE EQUIPMENT LIST,
   zone4[] Zone Equipment,   !- Name
   AIR DISTRIBUTION UNIT,   !- KEY--Zone Equipment Type 1
   zone4[] Term Reheat,      !- Type Name 1
   1,                    !- Cooling Priority
   1;                    !- Heating Priority

ZONE EQUIPMENT LIST,
   zone5[] Zone Equipment,   !- Name
   AIR DISTRIBUTION UNIT,   !- KEY--Zone Equipment Type 1
   zone5[] Term Reheat,      !- Type Name 1
   1,                    !- Cooling Priority
```

```
    1;                    !- Heating Priority

!-   ===========  ALL OBJECTS IN CLASS: AIR DISTRIBUTION UNIT ===========

AIR DISTRIBUTION UNIT,
    zone1[] Term Reheat,      !- Air Distribution Unit Name
    zone1[] Reheat air outlet node,  !- Air Dist Unit Outlet Node Name
    Single duct:VAV:reheat,  !- KEY--System Component Type 1
    zone1[] VAV Systerm;      !- Component Name 1

AIR DISTRIBUTION UNIT,
    zone2[] Term Reheat,      !- Air Distribution Unit Name
    zone2[] Reheat air outlet node,  !- Air Dist Unit Outlet Node Name
    Single duct:VAV:reheat,  !- KEY--System Component Type 1
    zone2[] VAV Systerm;      !- Component Name 1

AIR DISTRIBUTION UNIT,
    zone3[] Term Reheat,      !- Air Distribution Unit Name
    zone3[] Reheat air outlet node,  !- Air Dist Unit Outlet Node Name
    Single duct:VAV:reheat,  !- KEY--System Component Type 1
    zone3[] VAV Systerm;      !- Component Name 1

AIR DISTRIBUTION UNIT,
    zone4[] Term Reheat,      !- Air Distribution Unit Name
    zone4[] Reheat air outlet node,  !- Air Dist Unit Outlet Node Name
    Single duct:VAV:reheat,  !- KEY--System Component Type 1
    zone4[] VAV Systerm;      !- Component Name 1

AIR DISTRIBUTION UNIT,
    zone5[] Term Reheat,      !- Air Distribution Unit Name
    zone5[] Reheat air outlet node,  !- Air Dist Unit Outlet Node Name
    Single duct:VAV:reheat,  !- KEY--System Component Type 1
    zone5[] VAV Systerm;      !- Component Name 1

!-   ===========  ALL OBJECTS IN CLASS: SINGLE DUCT:VAV:REHEAT ===========

SINGLE DUCT:VAV:REHEAT,
    zone1[] VAV Systerm,      !- Name of System
    fansch[],        !- System Availability schedule
    zone1[] Reheat air inlet node,  !- DAMPER Air Outlet Node
    zone1[] Damper inlet node,!- UNIT Air Inlet Node
    zone1airflowrate[],                !- Maximum air flow rate {m3/s}
    .3,                   !- Zone Minimum Air Flow Fraction
    ,                    !- Control node
    Coil:Electric:Heating,   !- Reheat Component Object
    zone1[] Reheat Coil,      !- Name of Reheat Component
    0,                    !- Max Reheat Water Flow {m3/s}
    0,                    !- Min Reheat Water Flow {m3/s}
    zone1[] reheat air outlet node,  !- UNIT Air Outlet Node
    .001,                  !- Convergence Tolerance
    REVERSE ACTION;         !- Damper Heating Action

SINGLE DUCT:VAV:REHEAT,
    zone2[] VAV Systerm,      !- Name of System
    fansch[],        !- System Availability schedule
    zone2[] Reheat air inlet node,  !- DAMPER Air Outlet Node
    zone2[] Damper inlet node,!- UNIT Air Inlet Node
    zone2airflowrate[],                !- Maximum air flow rate {m3/s}
    .3,                   !- Zone Minimum Air Flow Fraction
    ,                    !- Control node
    Coil:Electric:Heating,   !- Reheat Component Object
    zone2[] Reheat Coil,      !- Name of Reheat Component
    0,                    !- Max Reheat Water Flow {m3/s}
    0,                    !- Min Reheat Water Flow {m3/s}
    zone2[] reheat air outlet node,  !- UNIT Air Outlet Node
    .001,                  !- Convergence Tolerance
    REVERSE ACTION;         !- Damper Heating Action

SINGLE DUCT:VAV:REHEAT,
    zone3[] VAV Systerm,      !- Name of System
    fansch[],        !- System Availability schedule
    zone3[] Reheat air inlet node,  !- DAMPER Air Outlet Node
    zone3[] Damper inlet node,!- UNIT Air Inlet Node
    zone3airflowrate[],                !- Maximum air flow rate {m3/s}
    .3,                   !- Zone Minimum Air Flow Fraction
```

```
    ,                    !- Control node
    Coil:Electric:Heating,   !- Reheat Component Object
    zone3[] Reheat Coil,      !- Name of Reheat Component
    0,                    !- Max Reheat Water Flow {m3/s}
    0,                    !- Min Reheat Water Flow {m3/s}
    zone3[] reheat air outlet node,  !- UNIT Air Outlet Node
    .001,                  !- Convergence Tolerance
    REVERSE ACTION;         !- Damper Heating Action

SINGLE DUCT:VAV:REHEAT,
    zone4[] VAV Systerm,      !- Name of System
    fansch[],         !- System Availability schedule
    zone4[] Reheat air inlet node,  !- DAMPER Air Outlet Node
    zone4[] Damper inlet node,!- UNIT Air Inlet Node
    zone4airflowrate[],                !- Maximum air flow rate {m3/s}
    .3,                   !- Zone Minimum Air Flow Fraction
    ,                    !- Control node
    Coil:Electric:Heating,   !- Reheat Component Object
    zone4[] Reheat Coil,      !- Name of Reheat Component
    0,                    !- Max Reheat Water Flow {m3/s}
    0,                    !- Min Reheat Water Flow {m3/s}
    zone4[] reheat air outlet node,  !- UNIT Air Outlet Node
    .001,                  !- Convergence Tolerance
    REVERSE ACTION;         !- Damper Heating Action

SINGLE DUCT:VAV:REHEAT,
    zone5[] VAV Systerm,      !- Name of System
    fansch[],         !- System Availability schedule
    zone5[] Reheat air inlet node,  !- DAMPER Air Outlet Node
    zone5[] Damper inlet node,!- UNIT Air Inlet Node
    zone5airflowrate[],                !- Maximum air flow rate {m3/s}
    .3,                   !- Zone Minimum Air Flow Fraction
    ,                    !- Control node
    Coil:Electric:Heating,   !- Reheat Component Object
    zone5[] Reheat Coil,      !- Name of Reheat Component
    0,                    !- Max Reheat Water Flow {m3/s}
    0,                    !- Min Reheat Water Flow {m3/s}
    zone5[] reheat air outlet node,  !- UNIT Air Outlet Node
    .001,                  !- Convergence Tolerance
    REVERSE ACTION;         !- Damper Heating Action

!-   ===========  ALL OBJECTS IN CLASS: COIL:ELECTRIC:HEATING ===========

COIL:Electric:Heating,
    zone1[] Reheat Coil,      !- Coil Name
    fansch[],         !- Available Schedule
    1,                    !- Efficiency of the Coil
    zone1reheatcoilcap[],                !- Nominal Capacity of the Coil {W}
    zone1[] Reheat air inlet node,  !- Coil_Air_Inlet_Node
    zone1[] Reheat air outlet node;  !- Coil_Air_Outlet_Node

COIL:Electric:Heating,
    zone2[] Reheat Coil,      !- Coil Name
    fansch[],         !- Available Schedule
    1,                    !- Efficiency of the Coil
    zone2reheatcoilcap[],                !- Nominal Capacity of the Coil {W}
    zone2[] Reheat air inlet node,  !- Coil_Air_Inlet_Node
    zone2[] Reheat air outlet node;  !- Coil_Air_Outlet_Node

COIL:Electric:Heating,
    zone3[] Reheat Coil,      !- Coil Name
    fansch[],         !- Available Schedule
    1,                    !- Efficiency of the Coil
    zone3reheatcoilcap[],                !- Nominal Capacity of the Coil {W}
    zone3[] Reheat air inlet node,  !- Coil_Air_Inlet_Node
    zone3[] Reheat air outlet node;  !- Coil_Air_Outlet_Node

COIL:Electric:Heating,
    zone4[] Reheat Coil,      !- Coil Name
    fansch[],         !- Available Schedule
    1,                    !- Efficiency of the Coil
    zone4reheatcoilcap[],                !- Nominal Capacity of the Coil {W}
    zone4[] Reheat air inlet node,  !- Coil_Air_Inlet_Node
    zone4[] Reheat air outlet node;  !- Coil_Air_Outlet_Node
```

```
COIL:Electric:Heating,
    zone5[] Reheat Coil,      !- Coil Name
    fansch[],        !- Available Schedule
    1,                    !- Efficiency of the Coil
    zone5reheatcoilcap[],               !- Nominal Capacity of the Coil {W}
    zone5[] Reheat air inlet node,  !- Coil_Air_Inlet_Node
    zone5[] Reheat air outlet node;  !- Coil_Air_Outlet_Node

!-   ===========  ALL OBJECTS IN CLASS: ZONE CONTROL:THERMOSTATIC ===========

ZONE CONTROL:THERMOSTATIC,
    zone1[] Thermostat,       !- Thermostat Name
    zone1[],               !- Zone Name
    zonecontrolsch[],   !- Control Type SCHEDULE Name
    Single Heating Setpoint, !- Control Type #1
    Heating_Setpoint[],        !- Control Type Name #1
    Single Cooling SetPoint, !- Control Type #2
    Cooling_Setpoint[],       !- Control Type Name #2
    Dual Setpoint with Deadband,  !- Control Type #3
    VAVSetpoint[];          !- Control Type Name #3

ZONE CONTROL:THERMOSTATIC,
   zone2[] Thermostat,       !- Thermostat Name
    zone2[],               !- Zone Name
    zonecontrolsch[],   !- Control Type SCHEDULE Name
    Single Heating Setpoint, !- Control Type #1
    Heating_Setpoint[],        !- Control Type Name #1
    Single Cooling SetPoint, !- Control Type #2
    Cooling_Setpoint[],       !- Control Type Name #2
    Dual Setpoint with Deadband,  !- Control Type #3
    VAVSetpoint[];          !- Control Type Name #3

ZONE CONTROL:THERMOSTATIC,
   zone3[] Thermostat,       !- Thermostat Name
    zone3[],               !- Zone Name
    zonecontrolsch[],   !- Control Type SCHEDULE Name
    Single Heating Setpoint, !- Control Type #1
    Heating_Setpoint[],        !- Control Type Name #1
    Single Cooling SetPoint, !- Control Type #2
    Cooling_Setpoint[],       !- Control Type Name #2
    Dual Setpoint with Deadband,  !- Control Type #3
    VAVSetpoint[];          !- Control Type Name #3

ZONE CONTROL:THERMOSTATIC,
    zone4[] Thermostat,       !- Thermostat Name
    zone4[],               !- Zone Name
    zonecontrolsch[],   !- Control Type SCHEDULE Name
    Single Heating Setpoint, !- Control Type #1
    Heating_Setpoint[],        !- Control Type Name #1
    Single Cooling SetPoint, !- Control Type #2
    Cooling_Setpoint[],       !- Control Type Name #2
    Dual Setpoint with Deadband,  !- Control Type #3
    VAVSetpoint[];          !- Control Type Name #3

ZONE CONTROL:THERMOSTATIC,
   zone5[] Thermostat,       !- Thermostat Name
   zone5[],               !- Zone Name
   zonecontrolsch[],   !- Control Type SCHEDULE Name
   Single Heating Setpoint, !- Control Type #1
   Heating_Setpoint[],        !- Control Type Name #1
   Single Cooling SetPoint, !- Control Type #2
   Cooling_Setpoint[],       !- Control Type Name #2
   Dual Setpoint with Deadband,  !- Control Type #3
   VAVSetpoint[];          !- Control Type Name #3

!-   ===========  ALL OBJECTS IN CLASS: ZONE SUPPLY AIR PATH ===========

ZONE SUPPLY AIR PATH,
    systemname[] zone supply air path, !- Supply Air Path Name
    systemname[] zone equip inlet node,!- Supply Air Path Inlet Node
    Zone Splitter,          !- KEY--System Component Type 1
    systemname[] Zone Supply air Splitter;  !- Component Name 1

!-   ===========  ALL OBJECTS IN CLASS: ZONE RETURN AIR PATH ===========
```

```
ZONE RETURN AIR PATH,
   systemname[] zone return air path, !- Return Air Path Name
   systemname[] return air mixer outlet node,  !- Return Air Path Outlet Node
   Zone mixer,            !- KEY--System Component Type 1
   systemname[] Zone return air mixer;!- Component Name 1

!-  ===========  ALL OBJECTS IN CLASS: ZONE SPLITTER ===========

ZONE SPLITTER,
   systemname[] Zone Supply air Splitter,  !- Splitter Name
   systemname[] zone equip inlet node,!- Inlet_Node
   zone1[] Damper inlet node,!- Outlet_Node_1
   zone2[] Damper inlet node,!- Outlet_Node_2
   zone3[] Damper inlet node,!- Outlet_Node_3
   zone4[] Damper inlet node,!- Outlet_Node_4
   zone5[] Damper inlet node;!- Outlet_Node_5

!-  ===========  ALL OBJECTS IN CLASS: ZONE MIXER ===========

ZONE MIXER,
   systemname[] Zone return air mixer,!- Mixer Name
   systemname[] Return air mixer outlet node,  !- Outlet_Node
   zone1[] outlet node,     !- Inlet_Node_1
   zone2[] outlet node,     !- Inlet_Node_2
   zone3[] outlet node,     !- Inlet_Node_3
   zone4[] outlet node,     !- Inlet_Node_4
   zone5[] outlet node;     !- Inlet_Node_5

!-  ===========  ALL OBJECTS IN CLASS: COIL:WATER:COOLING ===========

COIL:Water:Cooling,
   systemname[] Cooling Coil,        !- Coil Name
   fansch[],        !- Available Schedule
   autosize,              !- Design Water Flow Rate of Coil {m3/s}
   autosize,              !- Design Air Volume Flow Rate {m3/s}
   autosize,              !- Design Inlet Water Temperature {C}
   autosize,              !- Design Inlet Air Temperature {C}
   autosize,              !- Design Outlet Air Temperature {C}
   autosize,              !- Design Inlet Air Humidity Ratio {kg-H2O/kg-air}
   autosize,              !- Design Outlet Air Humidity Ratio {kg-H2O/kg-air}
   systemname[] Cooling Coil water inlet node,  !- Coil_Water_Inlet_Node
   systemname[] Cooling Coil water outlet node,  !- Coil_Water_Outlet_Node
   systemname[] Mixed air node,       !- Coil_Air_Inlet_Node
   systemname[] cooling coil air outlet node,  !- Coil_Air_Outlet_Node
   SIMPLEANALYSIS,         !- Type of Analysis
   CROSSFLOW;             !- Heat Exchanger Configuration

 !-  ===========  ALL OBJECTS IN CLASS: FAN:SIMPLE:VARIABLEVOLUME ===========

FAN:SIMPLE:VariableVolume,
   systemname[] Supply fan,          !- Fan Name
   fansch[],        !- Available Schedule
   fan_eff[],                  !- Fan Total Efficiency
   fan_delta_press[],                 !- Delta Pressure {Pa}
   maxairflowrate[],                !- Max Flow Rate {m3/s}
   minairflowrate[],                !- Min Flow Rate {m3/s}
   fan_motor_eff[],                 !- Motor Efficiency
   1,                  !- Motor In Airstream Fraction
   0.0015302446,           !- FanCoefficient 1
   0.0052080574,           !- FanCoefficient 2
   1.1086242,            !- FanCoefficient 3
   -0.11635563,           !- FanCoefficient 4
   0,                 !- FanCoefficient 5
   systemname[] cooling coil air outlet node,  !- Fan_Inlet_Node
   systemname[] air loop outlet node; !- Fan_Outlet_Node

##enddef

##include pump.idf
!****************************************************************
!              This module contains six numbers of Constant Air Cooled
!              Chillers
!
!              List of Variables:
!
```

```
!               pumpflowrate                        Rated Volumetric Flow Rate {m3/s}
!               pumphead                  Rated Pump Head {Pa}
!               pumppower                 Rated Power Consumption {W}
!               pumpeff                             Motor Efficiency
!******************************************************************

##def pump[]

!-  ===========  ALL OBJECTS IN CLASS: PUMP:VARIABLE SPEED ===========

PUMP:VARIABLE SPEED,
   CW Pump,                !- Pump Name
   CW supply inlet node,    !- Inlet_Node
   CW pump outlet node,     !- Outlet_Node
   pumpflowrate[],               !- Rated Volumetric Flow Rate {m3/s}
   pumphead[],                !- Rated Pump Head {Pa}
   pumppower[],                !- Rated Power Consumption {W}
   pumpeff[],                 !- Motor Efficiency
   0,                    !- Fraction of Motor Inefficiencies to Fluid Stream
   0,                    !- Coefficient1 of the Part Load Performance Curve
   1,                    !- Coefficient2 of the Part Load Performance Curve
   0,                    !- Coefficient3 of the Part Load Performance Curve
   0,                    !- Coefficient4 of the Part Load Performance Curve
   0,                    !- Min Flow Rate while operating in variable flow capacity {m3/s}
   INTERMITTENT;           !- Pump Control Type

!-  ===========  ALL OBJECTS IN CLASS: BRANCH ===========
 BRANCH,
    CW pump Branch,         !- Branch Name
    0,                    !- Maximum Branch Flow Rate {m3/s}
    Pump:variable speed,    !- Comp1 Type
    CW pump,               !- Comp1 Name
    CW supply inlet node,    !- Comp1 Inlet Node Name
    CW pump outlet node,     !- Comp1 Outlet Node Name
    ACTIVE;                !- Comp1 Branch Control Type

##enddef

##include chillerplant.idf

!-Generator IDFEditor 1.13

!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-     Use '!' comments if they need to be retained when using the IDFEditor.

!-  ===========  ALL OBJECTS IN CLASS: BRANCH LIST ===========
##def plant_branch_operation[]
! Chiller loop
BRANCH LIST,
   Cooling supply side branches,  !- Branch List Name
   CW pump Branch,         !- Branch Name 1
   Chiller no 1 branch,    !- Branch Name 2
   Chiller no 2 branch,    !- Branch Name 3
   Chiller no 3 branch,    !- Branch Name 4
   Chiller no 4 branch,    !- Branch Name 5
   Chiller no 5 branch,    !- Branch Name 6
   Chiller no 6 branch,    !- Branch Name 7
   CW supply Bypass Branch, !- Branch Name 8
   Cooling supply outlet branch;  !- Branch Name 9

BRANCH LIST,
   Cooling demand side branches,  !- Branch List Name
   Cooling demand inlet,    !- Branch Name 1
   GF cooling coil branch,  !- Branch Name 2
   20SP cooling coil branch,!- Branch Name 22
   RF cooling coil branch,  !- Branch Name 41
   Demand bypass branch,    !- Branch Name 42
   Cooling demand outlet;   !- Branch Name 43

!-  ===========  ALL OBJECTS IN CLASS: CONNECTOR LIST ===========

CONNECTOR LIST,
   Cooling supply side Connectors,  !- Connector List Name
   Splitter,              !- Type of Connector 1
   CW loop Splitter,       !- Name of Connector 1
```

```
  Mixer,                !- Type of Connector 2
  CW Loop mixer;        !- Name of Connector 2

CONNECTOR LIST,
  Cooling demand side connectors,  !- Connector List Name
  Splitter,             !- Type of Connector 1
  CW demand splitter,   !- Name of Connector 1
  Mixer,                !- Type of Connector 2
  CW Demand Mixer;      !- Name of Connector 2

!-  ===========  ALL OBJECTS IN CLASS: BRANCH ===========

BRANCH,
  Chiller no 1 branch,    !- Branch Name
  0,                      !- Maximum Branch Flow Rate {m3/s}
  chiller_type[],         !- Comp1 Type
  Chiller no 1,           !- Comp1 Name
  Chiller no 1 inlet node, !- Comp1 Inlet Node Name
  Chiller no 1 outlet node,!- Comp1 Outlet Node Name
  ACTIVE;                 !- Comp1 Branch Control Type

BRANCH,
  Chiller no 2 branch,    !- Branch Name
  0,                      !- Maximum Branch Flow Rate {m3/s}
  chiller_type[],         !- Comp1 Type
  Chiller no 2,           !- Comp1 Name
  Chiller no 2 inlet node, !- Comp1 Inlet Node Name
  Chiller no 2 outlet node,!- Comp1 Outlet Node Name
  ACTIVE;                 !- Comp1 Branch Control Type

BRANCH,
  Chiller no 3 branch,    !- Branch Name
  0,                      !- Maximum Branch Flow Rate {m3/s}
  chiller_type[],         !- Comp1 Type
  Chiller no 3,           !- Comp1 Name
  Chiller no 3 inlet node, !- Comp1 Inlet Node Name
  Chiller no 3 outlet node,!- Comp1 Outlet Node Name
  ACTIVE;                 !- Comp1 Branch Control Type

BRANCH,
  Chiller no 4 branch,    !- Branch Name
  0,                      !- Maximum Branch Flow Rate {m3/s}
  chiller_type[],         !- Comp1 Type
  Chiller no 4,           !- Comp1 Name
  Chiller no 4 inlet node, !- Comp1 Inlet Node Name
  Chiller no 4 outlet node,!- Comp1 Outlet Node Name
  ACTIVE;                 !- Comp1 Branch Control Type

BRANCH,
  Chiller no 5 branch,    !- Branch Name
  0,                      !- Maximum Branch Flow Rate {m3/s}
  chiller_type[],         !- Comp1 Type
  Chiller no 5,           !- Comp1 Name
  Chiller no 5 inlet node, !- Comp1 Inlet Node Name
  Chiller no 5 outlet node,!- Comp1 Outlet Node Name
  ACTIVE;                 !- Comp1 Branch Control Type

BRANCH,
  Chiller no 6 branch,    !- Branch Name
  0,                      !- Maximum Branch Flow Rate {m3/s}
  chiller_type[],         !- Comp1 Type
  Chiller no 6,           !- Comp1 Name
  Chiller no 6 inlet node, !- Comp1 Inlet Node Name
  Chiller no 6 outlet node,!- Comp1 Outlet Node Name
  ACTIVE;                 !- Comp1 Branch Control Type

BRANCH,
  Cooling supply outlet branch,  !- Branch Name
  0,                      !- Maximum Branch Flow Rate {m3/s}
  PIPE,                   !- Comp1 Type
  CW supply side outlet pipe,  !- Comp1 Name
  CW supply side exit pipe inlet node,  !- Comp1 Inlet Node Name
  CW supply side outlet node,  !- Comp1 Outlet Node Name
  PASSIVE;                !- Comp1 Branch Control Type
```

```
BRANCH,
   CW supply Bypass Branch, !- Branch Name
   0,                  !- Maximum Branch Flow Rate {m3/s}
   PIPE,               !- Comp1 Type
   CW supply side bypass,   !- Comp1 Name
   CW supply bypass inlet node,  !- Comp1 Inlet Node Name
   CW supply bypass outlet node,  !- Comp1 Outlet Node Name
   BYPASS;             !- Comp1 Branch Control Type

BRANCH,
   Cooling demand inlet,    !- Branch Name
   0,                  !- Maximum Branch Flow Rate {m3/s}
   Pipe,               !- Comp1 Type
   Demand side inlet pipe,  !- Comp1 Name
   cw demand inlet node,    !- Comp1 Inlet Node Name
   cw demand entrance pipe outlet node,  !- Comp1 Outlet Node Name
   PASSIVE;            !- Comp1 Branch Control Type

BRANCH,
   Demand bypass branch,    !- Branch Name
   0,                  !- Maximum Branch Flow Rate {m3/s}
   Pipe,               !- Comp1 Type
   Demand side bypass,      !- Comp1 Name
   CW demand bypass inlet node,  !- Comp1 Inlet Node Name
   CW demand bypass Outlet node,  !- Comp1 Outlet Node Name
   BYPASS;             !- Comp1 Branch Control Type

BRANCH,
   Cooling demand outlet,   !- Branch Name
   0,                  !- Maximum Branch Flow Rate {m3/s}
   Pipe,               !- Comp1 Type
   CW demand side outlet pipe,  !- Comp1 Name
   CW demand exit pipe inlet node,  !- Comp1 Inlet Node Name
   CW demand outlet node,   !- Comp1 Outlet Node Name
   PASSIVE;            !- Comp1 Branch Control Type

!-   ===========  ALL OBJECTS IN CLASS: PIPE ===========

PIPE,
   CW supply side bypass,   !- PipeName
   CW supply bypass inlet node,  !- Inlet Node Name
   CW supply bypass outlet node;  !- Outlet Node Name

PIPE,
   CW supply side outlet pipe,  !- PipeName
   CW supply side exit pipe inlet node,  !- Inlet Node Name
   CW supply side outlet node;  !- Outlet Node Name

PIPE,
   Demand side inlet pipe,  !- PipeName
   cw demand inlet node,    !- Inlet Node Name
   cw demand entrance pipe outlet node;  !- Outlet Node Name

PIPE,
   CW demand side outlet pipe,  !- PipeName
   CW demand exit pipe inlet node,  !- Inlet Node Name
   CW demand outlet node;   !- Outlet Node Name

PIPE,
   Demand side bypass,      !- PipeName
   CW demand bypass inlet node,  !- Inlet Node Name
   CW demand bypass Outlet node;  !- Outlet Node Name

!-   ===========  ALL OBJECTS IN CLASS: PLANT OPERATION SCHEMES ===========

PLANT OPERATION SCHEMES,
   CW Loop Operation,       !- PlantOperationSchemeName
   Load Range Based Operation,  !- KEY--Control Scheme 1
   On Peak operation,       !- Control Scheme Name 1
   On Peak;                 !- Control Scheme Schedule 1

!-   ===========  ALL OBJECTS IN CLASS: COOLING LOAD RANGE BASED OPERATION ===========

COOLING LOAD RANGE BASED OPERATION,
   On Peak operation,       !- Name
```

```
    0,                    !- Load Range Lower Limit 1 {W}
    capacity[],           !- Load Range Upper Limit 1 {W}
    One Chiller,          !- Priority Control Equip List Name 1
    capacity[],           !- Load Range Lower Limit 2 {W}
    #eval[2 * capacity[]],   !- Load Range Upper Limit 2 {W}
    Two Chillers,         !- Priority Control Equip List Name 2
    #eval[2 * capacity[]],   !- Load Range Lower Limit 3 {W}
    #eval[3 * capacity[]],   !- Load Range Upper Limit 3 {W}
    Three Chillers,       !- Priority Control Equip List Name 3
    #eval[3 * capacity[]],   !- Load Range Lower Limit 4 {W}
    #eval[4 * capacity[]],   !- Load Range Upper Limit 4 {W}
    Four Chillers,        !- Priority Control Equip List Name 4
    #eval[4 * capacity[]],   !- Load Range Lower Limit 5 {W}
    #eval[5 * capacity[]],   !- Load Range Upper Limit 5 {W}
    Five Chillers,        !- Priority Control Equip List Name 5
    #eval[5 * capacity[]],   !- Load Range Lower Limit 6 {W}
    #eval[99 * capacity[]],  !- Load Range Upper Limit 6 {W}
    Six Chillers;         !- Priority Control Equip List Name 6

!-   ===========  ALL OBJECTS IN CLASS: PLANT EQUIPMENT LIST ===========

PLANT EQUIPMENT LIST,
    One Chiller,          !- Equip List Name
    chiller_type[],       !- KEY--Plant Equip 1
    Chiller no 1;         !- Equip Name 1

PLANT EQUIPMENT LIST,
    Two Chillers,         !- Equip List Name
    chiller_type[],       !- KEY--Plant Equip 1
    Chiller no 1,         !- Equip Name 1
    chiller_type[],       !- KEY--Plant Equip 2
    Chiller no 2;         !- Equip Name 2

PLANT EQUIPMENT LIST,
    Three Chillers,       !- Equip List Name
    chiller_type[],       !- KEY--Plant Equip 1
    Chiller no 1,         !- Equip Name 1
    chiller_type[],       !- KEY--Plant Equip 2
    Chiller no 2,         !- Equip Name 2
    chiller_type[],       !- KEY--Plant Equip 3
    Chiller no 3;         !- Equip Name 3

PLANT EQUIPMENT LIST,
    Four Chillers,        !- Equip List Name
    chiller_type[],       !- KEY--Plant Equip 1
    Chiller no 1,         !- Equip Name 1
    chiller_type[],       !- KEY--Plant Equip 2
    Chiller no 2,         !- Equip Name 2
    chiller_type[],       !- KEY--Plant Equip 3
    Chiller no 3,         !- Equip Name 3
    chiller_type[],       !- KEY--Plant Equip 4
    Chiller no 4;         !- Equip Name 4

PLANT EQUIPMENT LIST,
    Five Chillers,        !- Equip List Name
    chiller_type[],       !- KEY--Plant Equip 1
    Chiller no 1,         !- Equip Name 1
    chiller_type[],       !- KEY--Plant Equip 2
    Chiller no 2,         !- Equip Name 2
    chiller_type[],       !- KEY--Plant Equip 3
    Chiller no 3,         !- Equip Name 3
    chiller_type[],       !- KEY--Plant Equip 4
    Chiller no 4,         !- Equip Name 4
    chiller_type[],       !- KEY--Plant Equip 5
    Chiller no 5;         !- Equip Name 5

PLANT EQUIPMENT LIST,
    Six Chillers,         !- Equip List Name
    chiller_type[],       !- KEY--Plant Equip 1
    Chiller no 1,         !- Equip Name 1
    chiller_type[],       !- KEY--Plant Equip 2
    Chiller no 2,         !- Equip Name 2
    chiller_type[],       !- KEY--Plant Equip 3
    Chiller no 3,         !- Equip Name 3
    chiller_type[],       !- KEY--Plant Equip 4
```

```
   Chiller no 4,          !- Equip Name 4
   chiller_type[],       !- KEY--Plant Equip 5
   Chiller no 5,          !- Equip Name 5
   chiller_type[],       !- KEY--Plant Equip 6
   Chiller no 6;          !- Equip Name 6

!-  ===========  ALL OBJECTS IN CLASS: SPLITTER ===========

SPLITTER,
   CW loop Splitter,       !- SplitterName
   CW pump Branch,          !- Inlet Branch Name
   Chiller no 1 branch,     !- Outlet Branch Name 1
   Chiller no 2 branch,     !- Outlet Branch Name 2
   Chiller no 3 branch,     !- Outlet Branch Name 3
   Chiller no 4 branch,     !- Outlet Branch Name 4
   Chiller no 5 branch,     !- Outlet Branch Name 5
   Chiller no 6 branch,     !- Outlet Branch Name 6
   CW supply Bypass Branch; !- Outlet Branch Name 7

SPLITTER,
   CW demand splitter,      !- SplitterName
   Cooling demand inlet,    !- Inlet Branch Name
   GF cooling coil branch,  !- Outlet Branch Name 1
   20SP cooling coil branch,!- Outlet Branch Name 21
   RF cooling coil branch,  !- Outlet Branch Name 40
   Demand bypass branch;    !- Outlet Branch Name 41

!-  ===========  ALL OBJECTS IN CLASS: MIXER ===========

MIXER,
   CW Loop mixer,          !- MixerName
   Cooling supply outlet branch,  !- Outlet Branch Name
   Chiller no 1 branch,     !- Inlet Branch Name 1
   Chiller no 2 branch,     !- Inlet Branch Name 2
   Chiller no 3 branch,     !- Inlet Branch Name 3
   Chiller no 4 branch,     !- Inlet Branch Name 4
   Chiller no 5 branch,     !- Inlet Branch Name 5
   Chiller no 6 branch,     !- Inlet Branch Name 6
   CW supply Bypass Branch; !- Inlet Branch Name 7

MIXER,
   CW Demand Mixer,        !- MixerName
   Cooling demand outlet,   !- Outlet Branch Name
   GF cooling coil branch,  !- Inlet Branch Name 1
   20SP cooling coil branch,!- Inlet Branch Name 21
   RF cooling coil branch,  !- Inlet Branch Name 40
   Demand bypass branch;    !- Inlet Branch Name 41

!-  ===========  ALL OBJECTS IN CLASS: SET POINT MANAGER:SCHEDULED ===========

SET POINT MANAGER:SCHEDULED,
   CW supply side outlet node manager,  !- Name
   TEMP,                  !- Control variable
   Chiller water supply temperature sch,  !- Schedule Name
   CW supply side outlet node;!- Name of the set point Node or Node List

##enddef

##include chillerCOP.idf
!***************************************************************
!              This module contains six numbers of Constant Air Cooled
!              Chillers
!
!              List of Variables:
!
!              capacity                  Nominal Capacity per chiller{W}
!              chiller_COP           COP
!              evaflowrate               Design Evaporator Volumetric Water
!                                                     Flow Rate {m3/s}
!              condflowrate              Design Condenser Volumetric Water
!                                                     Flow Rate {m3/s}
!              flowmode                  Constant or variable flow chiller
!***************************************************************

##def chiller[]
```

```
!-   ===========  ALL OBJECTS IN CLASS: CHILLER:CONST COP ===========

CHILLER:CONST COP,
    Chiller no 1,            !- Chiller Name
    capacity[],              !- Nominal Capacity {W}
    chiller_COP[],           !- COP
    evaflowrate[],           !- Design Evaporator Volumetric Water Flow Rate {m3/s}
    condflowrate[],          !- Design Condenser Volumetric Water Flow Rate {m3/s}
    Chiller no 1 inlet node, !- Plant_Side_Inlet_Node
    Chiller no 1 outlet node,!- Plant_Side_Outlet_Node
    Cold air inlet node,     !- Condenser_Side_Inlet_Node
    Cold air outlet node,    !- Condenser_Side_Outlet_Node
    Air Cooled,              !- Condenser Type
    flowmode[];              !- Chiller Flow Mode

CHILLER:CONST COP,
    Chiller no 2,            !- Chiller Name
    capacity[],              !- Nominal Capacity {W}
    chiller_COP[],           !- COP
    evaflowrate[],           !- Design Evaporator Volumetric Water Flow Rate {m3/s}
    condflowrate[],          !- Design Condenser Volumetric Water Flow Rate {m3/s}
    Chiller no 2 inlet node, !- Plant_Side_Inlet_Node
    Chiller no 2 outlet node,!- Plant_Side_Outlet_Node
    Cold air no 2 inlet node,!- Condenser_Side_Inlet_Node
    Cold air no 2 outlet node,  !- Condenser_Side_Outlet_Node
    Air Cooled,              !- Condenser Type
    flowmode[];              !- Chiller Flow Mode

CHILLER:CONST COP,
    Chiller no 3,            !- Chiller Name
    capacity[],              !- Nominal Capacity {W}
    chiller_COP[],           !- COP
    evaflowrate[],           !- Design Evaporator Volumetric Water Flow Rate {m3/s}
    condflowrate[],          !- Design Condenser Volumetric Water Flow Rate {m3/s}
    Chiller no 3 inlet node, !- Plant_Side_Inlet_Node
    Chiller no 3 outlet node,!- Plant_Side_Outlet_Node
    Cold air no 3 inlet node,!- Condenser_Side_Inlet_Node
    Cold air no 3 outlet node,  !- Condenser_Side_Outlet_Node
    Air Cooled,              !- Condenser Type
    flowmode[];              !- Chiller Flow Mode

CHILLER:CONST COP,
    Chiller no 4,            !- Chiller Name
    capacity[],              !- Nominal Capacity {W}
    chiller_COP[],           !- COP
    evaflowrate[],           !- Design Evaporator Volumetric Water Flow Rate {m3/s}
    condflowrate[],          !- Design Condenser Volumetric Water Flow Rate {m3/s}
    Chiller no 4 inlet node, !- Plant_Side_Inlet_Node
    Chiller no 4 outlet node,!- Plant_Side_Outlet_Node
    Cold air no 4 inlet node,!- Condenser_Side_Inlet_Node
    Cold air no 4 outlet node,  !- Condenser_Side_Outlet_Node
    Air Cooled,              !- Condenser Type
    flowmode[];              !- Chiller Flow Mode

CHILLER:CONST COP,
    Chiller no 5,            !- Chiller Name
    capacity[],              !- Nominal Capacity {W}
    chiller_COP[],           !- COP
    evaflowrate[],           !- Design Evaporator Volumetric Water Flow Rate {m3/s}
    condflowrate[],          !- Design Condenser Volumetric Water Flow Rate {m3/s}
    Chiller no 5 inlet node, !- Plant_Side_Inlet_Node
    Chiller no 5 outlet node,!- Plant_Side_Outlet_Node
    Cold air no 5 inlet node,!- Condenser_Side_Inlet_Node
    Cold air no 5 outlet node,  !- Condenser_Side_Outlet_Node
    Air Cooled,              !- Condenser Type
    flowmode[];              !- Chiller Flow Mode

CHILLER:CONST COP,
    Chiller no 6,            !- Chiller Name
    capacity[],              !- Nominal Capacity {W}
    chiller_COP[],           !- COP
    evaflowrate[],           !- Design Evaporator Volumetric Water Flow Rate {m3/s}
    condflowrate[],          !- Design Condenser Volumetric Water Flow Rate {m3/s}
    Chiller no 6 inlet node, !- Plant_Side_Inlet_Node
```

```
  Chiller no 6 outlet node,!- Plant_Side_Outlet_Node
  Cold air no 6 inlet node,!- Condenser_Side_Inlet_Node
  Cold air no 6 outlet node,  !- Condenser_Side_Outlet_Node
  Air Cooled,             !- Condenser Type
  flowmode[];             !- Chiller Flow Mode

##enddef
```

Appendix II – Modifications for Window Calculation Algorithm of EnergyPlus Program

The solar and visible properties of coated glazing were added into the "MODULE Window Manager" of EnergyPlus program by S.L. Wong and Ernest K.W. Tsang on September 2006.

```
MODULE WindowManager

    ! MODULE INFORMATION
    !    AUTHOR         Fred Winkelmann
    !    DATE WRITTEN   September 1999
    !    MODIFIED       August 2001 (FW): add window shade thermal calculation;
    !                   add window blind optical and thermal model.
    !             February 2003 (FW/LKL): Name changed to WindowManager
    !    RE-ENGINEERED  na
    ! PURPOSE OF THIS MODULE:
    ! Manages the window optical and thermal calculations derived
    ! from WINDOW 4 and WINDOW 5.
    ! METHODOLOGY EMPLOYED:
    !
    ! REFERENCES:
    ! WINDOW 4:
    ! D.Arasteh, M.Reilly and M.Rubin. A versative procedure for
    ! calculating heat transfer through windows. ASHRAE Trans. 1989, Vol. 95, Pt. 2.
    ! E.Finlayson, D.Arasteh, C.Huizenga, M.Rubin, and M.Reilly. WINDOW 4.0:
    ! Documentation of calculation procedures. LBL-33943. July 1993.
    ! WINDOW 5:
    ! ASHRAE Standard 142P (draft 1/13/98): Standard method for determining and expressing
    ! the heat transfer and total optical properties of fenestration products.
    ! Shade and blind thermal model:
    ! ISO/DIS 15099, Thermal Performance of Windows, Doors and Shading Devices,
    ! Detailed Calculations, 1/12/00.
    ! Blind optical model:
    ! H. Simmler, U. Fischer and Frederick Winkelmann, Solar-Thermal Window Blind Model
    ! for DOE-2, Lawrence Berkeley National Laboratory, Jan. 1996.
    ! USE STATEMENTS:
USE DataEnvironment
USE DataHeatBalance
USE DataHeatBalFanSys
USE DataGlobals
USE DataSurfaces
USE Vectors

IMPLICIT NONE       ! Enforce explicit typing of all variables

PRIVATE

    !MODULE PARAMETER DEFINITIONS:

REAL,    PRIVATE, PARAMETER :: sigma=5.6697e-8    ! Stefan-Boltzmann constant
REAL,    PRIVATE, PARAMETER :: errtemp=0.1        ! Convergence tolerance (K)
INTEGER, PRIVATE, PARAMETER :: maxspec=500        ! Maximum values in spectral data file
INTEGER, PRIVATE, PARAMETER :: maxlam=500         ! Maximum values in solar spectrum
INTEGER, PRIVATE, PARAMETER :: nume=107           ! Number of wavelength values in solar spectrum
INTEGER, PRIVATE, PARAMETER :: numt3=81           ! Number of wavelength values in the photopic response
```

```
REAL,    PRIVATE, PARAMETER, DIMENSION(8) :: AirProps=  &
!             Dens  dDens/dT  Con    dCon/dT   Vis    dVis/dT Prandtl dPrandtl/dT
           (/ 1.29, -0.4e-2, 2.41e-2, 7.6e-5, 1.73e-5, 1.0e-7, 0.72,   1.8e-3  /)
! Air mass 1.5 terrestrial solar global spectral irradiance (W/m2-micron)
! on a 37 degree tilted surface; corresponds
! to wavelengths (microns) in following data block (ISO 9845-1 and ASTM E 892;
! derived from Optics5 data file ISO-9845GlobalNorm.std, 10-14-99)
REAL, PRIVATE, PARAMETER, DIMENSION(nume) :: wle= &   ! Solar spectrum wavelength values (microns)
   (/0.3000,0.3050,0.3100,0.3150,0.3200,0.3250,0.3300,0.3350,0.3400,0.3450, &
     0.3500,0.3600,0.3700,0.3800,0.3900,0.4000,0.4100,0.4200,0.4300,0.4400, &
     0.4500,0.4600,0.4700,0.4800,0.4900,0.5000,0.5100,0.5200,0.5300,0.5400, &
     0.5500,0.5700,0.5900,0.6100,0.6300,0.6500,0.6700,0.6900,0.7100,0.7180, &
     0.7244,0.7400,0.7525,0.7575,0.7625,0.7675,0.7800,0.8000,0.8160,0.8237, &
     0.8315,0.8400,0.8600,0.8800,0.9050,0.9150,0.9250,0.9300,0.9370,0.9480, &
     0.9650,0.9800,0.9935,1.0400,1.0700,1.1000,1.1200,1.1300,1.1370,1.1610, &
     1.1800,1.2000,1.2350,1.2900,1.3200,1.3500,1.3950,1.4425,1.4625,1.4770, &
     1.4970,1.5200,1.5390,1.5580,1.5780,1.5920,1.6100,1.6300,1.6460,1.6780, &
     1.7400,1.8000,1.8600,1.9200,1.9600,1.9850,2.0050,2.0350,2.0650,2.1000, &
     2.1480,2.1980,2.2700,2.3600,2.4500,2.4940,2.5370 /)

REAL, PRIVATE, PARAMETER, DIMENSION(nume) :: e=  &  ! Solar spectrum values corresponding to wle
   (/   0.0,   9.5,  42.3, 107.8, 181.0, 246.0, 395.3, 390.1, 435.3, 438.9, &
      483.7, 520.3, 666.2, 712.5, 720.7,1013.1,1158.2,1184.0,1071.9,1302.0, &
     1526.0,1599.6,1581.0,1628.3,1539.2,1548.7,1586.5,1484.9,1572.4,1550.7, &
     1561.5,1501.5,1395.5,1485.3,1434.1,1419.9,1392.3,1130.0,1316.7,1010.3, &
     1043.2,1211.2,1193.9,1175.5, 643.1,1030.7,1131.1,1081.6, 849.2, 785.0, &
      916.4, 959.9, 978.9, 933.2, 748.5, 667.5, 690.3, 403.6, 258.3, 313.6, &
      526.8, 646.4, 746.8, 690.5, 637.5, 412.6, 108.9, 189.1, 132.2, 339.0, &
      460.0, 423.6, 480.5, 413.1, 250.2,  32.5,   1.6,  55.7, 105.1, 105.5, &
      182.1, 262.2, 274.2, 275.0, 244.6, 247.4, 228.7, 244.5, 234.8, 220.5, &
      171.5,  30.7,   2.0,   1.2,  21.2,  91.1,  26.8,  99.5,  60.4,  89.1, &
       82.2,  71.5,  70.2,  62.0,  21.2,  18.5,   3.2 /)

! Phototopic response function and corresponding wavelengths (microns)
! (CIE 1931 observer; ISO/CIE 10527, CIE Standard Calorimetric Observers;
! derived from Optics5 data file "CIE 1931 Color Match from E308.txt", which is
! the same as WINDOW4 file Cie31t.dat)
REAL, PRIVATE, PARAMETER, DIMENSION(numt3) :: wlt3=  &  ! Wavelength values for photopic response
   (/.380,.385,.390,.395,.400,.405,.410,.415,.420,.425, &
     .430,.435,.440,.445,.450,.455,.460,.465,.470,.475, &
     .480,.485,.490,.495,.500,.505,.510,.515,.520,.525, &
     .530,.535,.540,.545,.550,.555,.560,.565,.570,.575, &
     .580,.585,.590,.595,.600,.605,.610,.615,.620,.625, &
     .630,.635,.640,.645,.650,.655,.660,.665,.670,.675, &
     .680,.685,.690,.695,.700,.705,.710,.715,.720,.725, &
     .730,.735,.740,.745,.750,.755,.760,.765,.770,.775, &
     .780 /)

REAL, PRIVATE, PARAMETER, DIMENSION(numt3) :: y30=  &   ! Photopic response corresponding to wavelengths in
wlt3
   (/0.0000,0.0001,0.0001,0.0002,0.0004,0.0006,0.0012,0.0022,0.0040,0.0073, &
     0.0116,0.0168,0.0230,0.0298,0.0380,0.0480,0.0600,0.0739,0.0910,0.1126, &
     0.1390,0.1693,0.2080,0.2586,0.3230,0.4073,0.5030,0.6082,0.7100,0.7932, &
     0.8620,0.9149,0.9540,0.9803,0.9950,1.0000,0.9950,0.9786,0.9520,0.9154, &
     0.8700,0.8163,0.7570,0.6949,0.6310,0.5668,0.5030,0.4412,0.3810,0.3210, &
     0.2650,0.2170,0.1750,0.1382,0.1070,0.0816,0.0610,0.0446,0.0320,0.0232, &
     0.0170,0.0119,0.0082,0.0158,0.0041,0.0029,0.0021,0.0015,0.0010,0.0007, &
     0.0005,0.0004,0.0002,0.0002,0.0001,0.0001,0.0001,0.0000,0.0000,0.0000, &
     0.0000 /)

        ! MODULE VARIABLE DECLARATIONS:

REAL           :: height                ! Window height (m)
INTEGER        :: ngllayer              ! Number of glass layers
INTEGER        :: nglface               ! Number of glass faces
INTEGER        :: nglfacep              ! Number of glass faces, + 2 if shade layer present
INTEGER        :: iwd                   ! Wind direction  [0 - windward; 1 - leeward]
INTEGER        :: constr                ! Calculation contraints
INTEGER        :: ierrcd                ! Error code
REAL           :: tout                  ! Outside air temperature (K)
DOUBLE PRECISION  :: tin                ! Inside air temperature (previous timestep) (K)
REAL           :: tinrad                ! Radiant room temperature seen by window (K)
REAL           :: ws                    ! Wind speed (m/s)
REAL           :: windin                ! Inside forced air speed (m/s)
REAL           :: dir                   ! Direct solar radiation (W/m2)
```

```
REAL            :: totsol                   ! Total solar transmittance
REAL            :: tilt                     ! Window tilt (deg)
REAL            :: tiltr                    ! Window tilt (radians)
REAL            :: hflux                    ! Net heat flux between room and window
REAL            :: shgf                     ! Solar heat gain factor
REAL            :: hcin                     ! Convective inside air film conductance (W/m2-K)
REAL            :: hcout                    ! Convective outside air film conductance (W/m2-K)
REAL            :: hrin                     ! Inside effective IR radiation conductance
REAL            :: hrout                    ! Outside effective IR radiation conductance
REAL            :: Ebout                    ! Sigma*(outside air temp)**4 (W/m2)
REAL            :: Outir                    ! IR radiance of window's exterior surround (W/m2)
REAL            :: Rmir                     ! IR radiance of window's interior surround (W/m2)
REAL            :: dtmax                    ! Maximum temperature difference between iterations (K)
REAL            :: rtot                     ! Total thermal resistance of window (m2-K/W)
REAL            :: flux                     ! Net heat flux at inside surface [W/m2]
REAL            :: gcon(5,5,3) =0.0         ! Gas thermal conductivity coefficients for each gap
REAL            :: gvis(5,5,3) =0.0         ! Gas viscosity coefficients for each gap
REAL            :: gcp(5,5,3)  =0.0         ! Gas specific-heat coefficients for each gap
REAL            :: gwght(5,5)  =0.0         ! Gas molecular weights for each gap
REAL            :: gfract(5,5) =0.0         ! Gas fractions for each gap
INTEGER         :: gnmix(5)    =0           ! Number of gases in gap
REAL            :: gap(5)      =0.0         ! Gap width (m)
REAL            :: thick(5)    =0.0         ! Glass layer thickness (m)
REAL            :: scon(5)     =0.0         ! Glass layer conductance--conductivity/thickness (W/m2-K)
REAL            :: tir(10)     =0.0         ! Front and back IR transmittance for each glass layer
REAL            :: emis(10)    =0.0         ! Front and back IR emissivity for each glass layer
REAL            :: rir(10)     =0.0         ! Front and back IR reflectance for each glass layer
                                            !  (program calculates from tir and emis)
REAL            :: AbsRadGlassFace(10) =0.0     ! Solar radiation and IR radiation from internal
                                            !  gains absorbed by glass face
DOUBLE PRECISION  :: thetas(10)         =0.0D0   ! Glass surface temperatures (K)
DOUBLE PRECISION  :: thetasPrev(10)     =0.0D0   ! Previous-iteration glass surface temperatures (K)
DOUBLE PRECISION  :: fvec(10)           =0.0D0   ! Glass face heat balance function
DOUBLE PRECISION  :: fjac(10,10)        =0.0D0   ! Glass face heat balance Jacobian
REAL            :: dtheta(5)        =0.0    ! Glass layer temperature difference factor [K]
REAL            :: zir(10,10)       =0.0    ! IR transfer matrix
REAL            :: ziri(10,10)      =0.0    ! Inverse of IR transfer matrix
REAL            :: ddeldt(10,10)    =0.0    ! Matrix of derivatives of residuals wrt temperature
REAL            :: dtddel(10,10)    =0.0    ! Inverse of matrix of derivatives of
                                            !   residuals wrt temperature
REAL            :: qf(10)           =0.0    ! IR heat flux at each face [W/m2]
REAL            :: hf(10)           =0.0    ! Component of convective flux at each face
REAL            :: der(10,5)        =0.0    ! Derivative of IR sources wrt surface temperature
REAL            :: dhf(10,5)        =0.0    ! Derivative of heat flux wrt surface temperature
REAL            :: sour(10)         =0.0    ! IR source term at each face [W/m2]
REAL            :: delta(5)         =0.0    ! Residual at each glass layer [W/m2]
REAL            :: hcgap(5)         =0.0    ! Convective gap conductance
REAL            :: hrgap(5)         =0.0    ! Radiative gap conductance
REAL            :: rgap(6)          =0.0    ! Convective plus radiative gap resistance
                                            !   (inverse of hcgap + hrgap)
REAL            :: rs(6)            =0.0    ! Outside film convective resistance, gap resistances,
                                            !   inside air film convective resistance
REAL            :: arhs(6)          =0.0
INTEGER         :: indexiter                ! Iteration number
INTEGER         :: dflag
REAL            :: A23P,A32P,A45P,A54P,A67P,A76P ! Intermediate variables in glass face
REAL            :: A23,A45,A67              ! heat balance equations
REAL            :: wlt(maxspec,5)     =0.0    ! Spectral data wavelengths for each
                                            !  glass layer in a glazing system
REAL            :: t(maxspec,5)       =0.0    ! For each layer, normal transmittance for each
                                            !  wavelength in wlt
REAL            :: rff(maxspec,5)     =0.0    ! For each layer, normal front reflectance for each
                                            !  wavelength in wlt
REAL            :: rbb(maxspec,5)     =0.0    ! For each layer, normal back reflectance for each
                                            !  wavelength in wlt
REAL            :: tPhi(maxspec,5)    =0.0    ! For each layer, transmittance at angle of incidence
                                            !  for each wavelength in wlt
REAL            :: rfPhi(maxspec,5)   =0.0    ! For each layer, front reflectance at angle of incidence
                                            !  for each wavelength in wlt
REAL            :: rbPhi(maxspec,5)   =0.0    ! For each layer, back reflectance at angle of incidence
                                            !  for each wavelength in wlt
REAL            :: tadjPhi(maxspec,5)  =0.0    ! For each layer, transmittance at angle of incidence
                                            !  for each wavelength in wle
REAL            :: rfadjPhi(maxspec,5) =0.0    ! For each layer, front reflectance at angle of incidence
                                            !  for each wavelength in wle
```

```
REAL           :: rbadjPhi(maxspec,5) =0.0    ! For each layer, back reflectance at angle of incidence
                             !  for each wavelength in wle
INTEGER        :: numpt(5)          =0      ! Number of spectral data wavelengths for each layer;
                             !  =2 if no spectra data for a layer
REAL           :: stPhi(nume)       =0.0    ! Glazing system transmittance at angle of incidence
                             !  for each wavelength in wle
REAL           :: srfPhi(nume)      =0.0    ! Glazing system front reflectance at angle of incidence
                             !  for each wavelength in wle
REAL           :: srbPhi(nume)      =0.0    ! Glazing system back reflectance at angle of incidence
                             !  for each wavelenth in wle
REAL           :: saPhi(nume,5)     =0.0    ! For each layer, glazing system absorptance at angle of incidence
                             !  for each wavelenth in wle
REAL           :: top(5,5)          =0.0    ! Transmittance matrix for subr. op
REAL           :: rfop(5,5)         =0.0    ! Front reflectance matrix for subr. op
REAL           :: rbop(5,5)         =0.0    ! Back transmittance matrix for subr. op
REAL           :: IndepVarCurveFit(10)=0.0    ! Values of independent variable (cos of inc. angle) for curve fit
REAL           :: DepVarCurveFit(10)  =0.0    ! Values of dependent variable corresponding
                             !  to IndepVarCurveFit values
REAL           :: CoeffsCurveFit(6)   =0.0    ! Polynomial coefficients from curve fit
REAL           :: tsolPhi(10)       =0.0    ! Glazing system solar transmittance for each angle of incidence
REAL           :: rfsolPhi(10)      =0.0    ! Glazing system solar front reflectance for each angle of incidence
REAL           :: rbsolPhi(10)      =0.0    ! Glazing system solar back reflectance for each angle of incidence
REAL           :: solabsPhi(10,5)   =0.0    ! Glazing system solar absorptance for each angle of incidence
REAL           :: solabsBackPhi(10,5) =0.0    ! Glazing system back solar absorptance for each angle of incidence
REAL           :: solabsShadePhi(10)  =0.0    ! Glazing system interior shade solar absorptance for each angle of
                             ! incidence
REAL           :: tvisPhi(10)       =0.0    ! Glazing system visible transmittance for each angle of incidence
REAL           :: rfvisPhi(10)      =0.0    ! Glazing system visible front reflectance for each angle of
                             ! incidence
REAL           :: rbvisPhi(10)      =0.0    ! Glazing system visible back reflectance for each angle of
                             ! incidence
REAL           :: CosPhiIndepVar(10)  =0.0    ! Cos of incidence angles at 10-deg increments for curve fits

    ! SUBROUTINE SPECIFICATIONS FOR MODULE WindowManager
PUBLIC  InitGlassOpticalCalculations
PUBLIC  CalcWindowHeatBalance
PUBLIC  W5LsqFit

CONTAINS
    ! MODULE SUBROUTINES:

SUBROUTINE InitGlassOpticalCalculations

    ! SUBROUTINE INFORMATION:
    !     AUTHOR         F. Winkelmann
    !     DATE WRITTEN   August 1999
    !     MODIFIED       May 2001 (FW): add window blinds
    !                    Jan 2002 (FW): add blinds with variable slat angle
    !                    Jan 2003 (FW): add between-glass shade/blind
    !     RE-ENGINEERED  na
    ! PURPOSE OF THIS SUBROUTINE
    ! Manages the calculation of the solar and visible properties of a multi-layer glazing
    ! system from the properties of the individual glazing and shading layers
    ! METHODOLOGY EMPLOYED
    ! na
    ! REFERENCES
    ! na

 IMPLICIT NONE    ! Enforce explicit typing of all variables in this routine

    ! SUBROUTINE LOCAL VARIABLE DECLARATIONS

INTEGER        :: CoefNum             ! Polynomial coefficient number
INTEGER        :: j                   ! Wavelength counter
INTEGER        :: TotLay              ! Total solid and gas layers in a window construction
INTEGER        :: ConstrNum           ! Construction number
INTEGER        :: ConstrNumSh         ! Shaded construction number
INTEGER        :: SurfNum             ! Surface number
INTEGER        :: ShadeLayNum         ! Layer number for shade or blind, if present
INTEGER        :: ShadeLayPtr         ! Material number for shade or blind
LOGICAL        :: lquasi              ! True if one or more glass layers have no spectral data
LOGICAL        :: AllGlassIsSpectralAverage ! True if all glazing in a construction is spectral average
LOGICAL        :: IntShade,ExtShade,BGShade ! True if construction has an interior,exterior or between-glass shade
LOGICAL        :: IntBlind,ExtBlind,BGBlind ! True if construction has an interior,exterior or between-glass blind
LOGICAL        :: BlindOn             ! True if IntBlind, ExtBlind or BGBlind is true
```

```
LOGICAL        :: ShadeOn              ! True if IntShade, ExtShade or BGShade is true
INTEGER        :: BlNum                ! Blind number
REAL           :: sabsPhi(nume)        ! Glazing system absorptance for a glass layer
                        !  and angle of incidence, for each wavelength
                        !   glass layer for an angle of incidence, for each wavelength


!==========================================================================================
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!     The following is added by S.L. Wong and Ernest K.W. Tsang
!     on 12th September 2006
LOGICAL             :: solarfilm(5)              ! True if it is solar film
LOGICAL             :: WindowFilm                  ! True if it involve any solar film layer
!==========================================================================================
=====

REAL           :: solabsDiff(5)          ! Glazing system layer solar absorptance for each glass layer
REAL           :: solabsPhiLay(10)       ! Glazing system solar absorptance for a layer at each incidence angle
REAL           :: tsolPhiFit(10)         ! Glazing system solar transmittance from fit at each incidence angle
REAL           :: tvisPhiFit(10)         ! Glazing system visible transmittance from fit at each incidence angle
REAL           :: tBareSolPhi(10,5)      ! Isolated glass solar transmittance for each incidence angle
REAL           :: t1,t2                  ! = tBareSolPhi(,1)(,2)
REAL           :: tBareVisPhi(10,5)      ! Isolated glass visible transmittance for each incidence angle
REAL           :: t1v,t2v                ! = tBareVisPhi(,1)(,2)
REAL           :: rfBareSolPhi(10,5)     ! Isolated glass front solar reflectance for each incidence angle
REAL           :: rfBareVisPhi(10,5)     ! Isolated glass front visible reflectance for each incidence angle
REAL           :: rbBareSolPhi(10,5)     ! Isolated glass back solar reflectance for each incidence angle
REAL           :: rbBareVisPhi(10,5)     ! Isolated glass back visible reflectance for each incidence angle
REAL           :: afBareSolPhi(10,5)     ! Isolated glass front solar absorptance for each incidence angle
REAL           :: af1,af2                ! = afBareSolPhi(,1)(,2)
REAL           :: rbmf2                  ! Isolated glass #2 front beam reflectance
REAL           :: abBareSolPhi(10,5)     ! Isolated glass back solar absorptance for each incidence angle
REAL           :: ab1,ab2                ! = abBareSolPhi(,1)(,2)
REAL           :: td1,td2,td3            ! Isolated glass diffuse solar transmittance
REAL           :: td1v,td2v,td3v         ! Isolated glass diffuse visible transmittance
REAL           :: rf1,rf2,rf3            ! Isolated glass diffuse solar front reflectance
REAL           :: rf1v,rf2v,rf3v         ! Isolated glass diffuse visible front reflectance
REAL           :: rb1,rb2,rb3            ! Isolated glass diffuse solar back reflectance
REAL           :: rb1v,rb2v,rb3v         ! Isolated glass diffuse visible back reflectance
REAL           :: afd1,afd2,afd3         ! Isolated glass diffuse solar front absorptance
REAL           :: abd1,abd2,abd3         ! Isolated glass diffuse solar back absorptance
REAL           :: TauShIR                ! IR transmittance of isolated shade
REAL           :: EpsShIR                ! IR absorptance of isolated shade
REAL           :: RhoShIR                ! IR reflectance of isolated shade
REAL           :: EpsGlIR                ! IR absorptance of front or back of isolated glass
REAL           :: RhoGlIR                ! IR reflectance of inside face of inside glass
INTEGER        :: NGlass                 ! Number of glass layers in a construction
INTEGER        :: IGlass                 ! Glass layer counter
INTEGER        :: LayNum                 ! Layer number for a glass layer
INTEGER        :: LayPtr                 ! Material number corresponding to LayNum
INTEGER        :: IPhi                   ! Incidence angle counter
REAL           :: Phi                    ! Incidence angle (deg)
REAL           :: CosPhi                 ! Cosine of incidence angle
INTEGER        :: ILam                   ! Wavelength counter
REAL           :: tsolDiff               ! Glazing system diffuse solar transmittance
REAL           :: tvisDiff               ! Glazing system diffuse visible transmittance
INTEGER        :: IGlassBack             ! Glass layer number counted from back of window
REAL           :: ShadeAbs               ! Solar absorptance of isolated shade
REAL           :: ash                    ! = ShadeAbs
REAL           :: afsh                   ! Diffuse solar front absorptance of isolated blind
REAL           :: afshGnd,afshSky        ! Ground and sky diffuse solar front absorptance of isolated blind
REAL           :: absh                   ! Diffuse solar back absorptance of isolated blind
REAL           :: ShadeTrans             ! Solar transmittance of isolated shade/blind
REAL           :: ShadeTransGnd          ! Diffuse-diffuse transmittance of isolated vertical blind with
                        ! horizontal slats for isotropic ground solar
REAL           :: ShadeTransSky          ! Diffuse-diffuse transmittance of isolated vertical blind with
                        ! horizontal slats for isotropic sky solar
REAL           :: tsh                    ! = ShadeTrans
REAL           :: tshGnd,tshSky          ! = ShadeTransGnd,ShadeTransSky
REAL           :: tsh2                   ! = tsh**2
REAL           :: ShadeRefl              ! Solar reflectance of isolated shade
REAL           :: ShadeReflGnd           ! Front blind reflectance for ground diffuse solar
REAL           :: ShadeReflSky           ! Front blind reflectance for sky diffuse solar
REAL           :: rsh                    ! = ShadeRefl
REAL           :: rfsh                   ! Diffuse solar front reflectance of isolated blind
```

```
REAL          :: rfshGnd,rfshSky        ! Ground and sky diffuse solar front reflectance of isolated blind
REAL          :: rbsh                   ! Diffuse solar back reflectance of isolated blind
REAL          :: ShadeReflFac           ! Shade/blind solar reflection factor
REAL          :: ShadeTransVis          ! Visible transmittance of isolated shade/blind
REAL          :: tshv                   ! = ShadeTransVis
REAL          :: tshv2                  ! = tshv**2
REAL          :: ShadeReflVis           ! Visible reflectance of isolated shade
REAL          :: rshv                   ! = ShadeReflVis
REAL          :: rfshv                  ! Diffuse visible front reflectance of isolated blind
REAL          :: rbshv                  ! Diffuse visible back reflectance of isolated blind
REAL          :: ShadeReflFacVis        ! Shade/blind visible reflection factor
INTEGER       :: SpecDataNum            ! Spectral data set number
INTEGER       :: numptDAT               ! Number of wavelengths in a spectral data set
INTEGER       :: ISlatAng               ! Slat angle counter
LOGICAL       :: StormWinConst          ! True if a construction with a storm window
LOGICAL       :: Triangle               ! True if window is triangular
LOGICAL       :: Rectangle              ! True if window is rectangular
REAL          :: W1(3),W2(3),W3(3)      ! Window vertices (m)
REAL          :: W21(3),W23(3)          ! W1-W2, W3-W2, resp. (m)

CALL W5InitGlassParameters

! Calculate optical properties of blind-type layers entered with MATERIAL:WindowBlind

IF(TotBlinds > 0) CALL CalcWindowBlindProperties

! Get glazing system optical properties of constructions with glass or glass plus
!   shade or blind
! Loop over constructions and find those that are glazing constructions
DO ConstrNum = 1,TotConstructs
  IF (.not. Construct(ConstrNum)%TypeIsWindow) CYCLE
  TotLay = Construct(ConstrNum)%TotLayers
  ! First layer must be glass, shade or blind to be a glazing construction
  IF(Material(Construct(ConstrNum)%LayerPoint(1))%Group /= WindowGlass .AND.  &
     Material(Construct(ConstrNum)%LayerPoint(1))%Group /= Shade .AND. &
     Material(Construct(ConstrNum)%LayerPoint(1))%Group /= WindowBlind) CYCLE
  ShadeLayNum = 0
  ExtShade = .FALSE.
  IntShade = .FALSE.
  BGShade  = .FALSE.
  ExtBlind = .FALSE.
  IntBlind = .FALSE.
  BGBlind  = .FALSE.
  StormWinConst = .false.
  IF(Construct(ConstrNum)%Name(1:28)=='BARECONSTRUCTIONWITHSTORMWIN' .OR.  &
     Construct(ConstrNum)%Name(1:30)=='SHADEDCONSTRUCTIONWITHSTORMWIN') StormWinConst = .true.

  ! Get layer number of shade/blind
  IF(Material(Construct(ConstrNum)%LayerPoint(1))%Group == Shade) THEN
    ExtShade = .TRUE.
    ShadeLayNum = 1
  ELSE IF(Material(Construct(ConstrNum)%LayerPoint(TotLay))%Group == Shade) THEN
    IntShade = .TRUE.
    ShadeLayNum = TotLay
  ELSE IF(Construct(ConstrNum)%TotLayers == 5) THEN
    IF (Material(Construct(ConstrNum)%LayerPoint(3))%Group == Shade) THEN
      BGShade  = .TRUE.
      ShadeLayNum = 3
    ENDIF
  ELSE IF(Construct(ConstrNum)%TotLayers == 7) THEN
    IF (Material(Construct(ConstrNum)%LayerPoint(5))%Group == Shade) THEN
      BGShade  = .TRUE.
      ShadeLayNum = 5
    ENDIF
  ENDIF

  IF(Material(Construct(ConstrNum)%LayerPoint(1))%Group == WindowBlind) THEN
    ExtBlind = .TRUE.
    ShadeLayNum = 1
    BlNum = Material(Construct(ConstrNum)%LayerPoint(ShadeLayNum))%BlindDataPtr
  ELSE IF(Material(Construct(ConstrNum)%LayerPoint(TotLay))%Group == WindowBlind) THEN
    IntBlind = .TRUE.
    ShadeLayNum = TotLay
    BlNum = Material(Construct(ConstrNum)%LayerPoint(ShadeLayNum))%BlindDataPtr
  ELSE IF(Construct(ConstrNum)%TotLayers == 5) THEN
```

```
  IF (Material(Construct(ConstrNum)%LayerPoint(3))%Group == WindowBlind) THEN
    BGBlind  = .TRUE.
    ShadeLayNum = 3
    BlNum = Material(Construct(ConstrNum)%LayerPoint(ShadeLayNum))%BlindDataPtr
  ENDIF
ELSE IF(Construct(ConstrNum)%TotLayers == 7) THEN
  IF (Material(Construct(ConstrNum)%LayerPoint(5))%Group == WindowBlind) THEN
    BGBlind  = .TRUE.
    ShadeLayNum = 5
    BlNum = Material(Construct(ConstrNum)%LayerPoint(ShadeLayNum))%BlindDataPtr
  ENDIF
END IF

BlindOn = IntBlind.OR.ExtBlind.OR.BGBlind
ShadeOn = IntShade.OR.ExtShade.OR.BGShade

! For construction with interior or exterior shade, get shade thermal absorptance (emissivity)
! (accounting for inter-reflection with glazing) and correct the inside glass InsideAbsorpThermal
! for presence of interior shade. Assumes inner and outer glass layers have zero thermal transmittance.

IF(IntShade.OR.ExtShade) THEN
  ShadeLayPtr = Construct(ConstrNum)%LayerPoint(ShadeLayNum)
  TauShIR = Material(ShadeLayPtr)%TransThermal
  EpsShIR = Material(ShadeLayPtr)%AbsorpThermal
  RhoShIR = MAX(0.,1-TauShIR-EpsShIR)
  IF(ExtShade) THEN  ! Exterior shade
    EpsGlIR = Material(Construct(ConstrNum)%LayerPoint(2))%AbsorpThermalBack
  ELSE              ! Interior shade
    EpsGlIR = Material(Construct(ConstrNum)%LayerPoint(TotLay-1))%AbsorpThermalBack
  END IF
  RhoGlIR = MAX(0.,1-EpsGlIR)
  Construct(ConstrNum)%ShadeAbsorpThermal = EpsShIR*(1+TauShIR*RhoGlIR/(1-RhoShIR*RhoGlIR))
  IF(IntShade) Construct(ConstrNum)%InsideAbsorpThermal = &
              Construct(ConstrNum)%InsideAbsorpThermal*TauShIR/(1-RhoShIR*RhoGlIR)
END IF

! From the individual glass layer properties, get the glazing system optical properties
! for BARE GLASS (i.e., interior, exterior or between-glass shade or blind, if present, not in place).
! Get one set of system properties for solar incident on front of
! window and a second set for solar incident on back of window. (The back-incident
! properties are used with interior short-wave radiation striking the window from inside.)

! After the front and back system optical properties are calculated for bare glass,
! a correction is made for the effect of a shade or blind if one of these
! is present in the construction.

NGlass = Construct(ConstrNum)%TotGlassLayers

!-------------------------------------------------------------------------------------------
! Front calculation (solar incident from outside of room); bare glass portion of construction
!-------------------------------------------------------------------------------------------

lquasi = .FALSE.
AllGlassIsSpectralAverage = .TRUE.

! Loop over glass layers in the construction

DO IGlass = 1,NGlass
  LayNum = 1 + 2*(IGlass-1)
  IF(ExtShade.OR.ExtBlind) LayNum = 2 + 2*(IGlass-1)
  IF(BGShade.OR.BGBlind) THEN
    LayNum = 1
    IF(NGlass==2) THEN
      IF(IGlass==2) LayNum = 5
    ELSE  ! NGlass = 3
      IF(IGlass==2) LayNum = 3
      IF(IGlass==3) LayNum = 7
    END IF
  END IF
  LayPtr = Construct(ConstrNum)%LayerPoint(LayNum)
  SpecDataNum = Material(LayPtr)%GlassSpectralDataPtr
  IF(SpecDataNum /= 0) THEN
    AllGlassIsSpectralAverage = .FALSE.
    ! Get the spectral data for the transmittance, front reflectance and
    ! back reflectance (all at normal incidence) for this layer.
```

```
    ! In this case, "front" means incident from the outside and "back"
    ! means incident from the inside.
    numptDAT = SpectralData(SpecDataNum)%NumOfWavelengths
    numpt(IGlass) = numptDat

    DO ILam = 1,numptDat
      wlt(ILam,IGlass) = SpectralData(SpecDataNum)%Wavelength(ILam)
      t(ILam,IGlass)   = SpectralData(SpecDataNum)%Trans(ILam)
      IF(IGlass==1.OR.(IGlass==2.AND.StormWinConst)) t(ILam,IGlass) = &
         t(ILam,IGlass) * Material(LayPtr)%GlassTransDirtFactor
      rff(ILam,IGlass) = SpectralData(SpecDataNum)%ReflFront(ILam)
      rbb(ILam,IGlass) = SpectralData(SpecDataNum)%ReflBack(ILam)
    END DO

  ELSE  ! No spectral data for this layer; use spectral average values
    lquasi = .TRUE.

!===========================================================================
!     The following is added by S.L. Wong and  Ernest K.W. Tsang
!        on 12th September 2006
        solarfilm(IGlass) = .FALSE.
!===========================================================================


    numpt(IGlass) = 2
    t(1,IGlass)   = Material(LayPtr)%Trans
    IF(IGlass==1.OR.(IGlass==2.AND.StormWinConst)) t(1,IGlass) =  &
       t(1,IGlass) * Material(LayPtr)%GlassTransDirtFactor
    t(2,IGlass)   = Material(LayPtr)%TransVis
    IF(IGlass==1.OR.(IGlass==2.AND.StormWinConst)) t(2,IGlass) =  &
       t(2,IGlass) * Material(LayPtr)%GlassTransDirtFactor


!===========================================================================
!        The followings are added by S.L. Wong and Ernest K.W. Tsang
!        on 12th September 2006
         IF (Material(LayPtr)%Name(1:4) == 'FILM') THEN
              solarfilm(IGlass) = .TRUE.
         ELSE
              solarfilm(IGlass) = .FALSE.
         END IF
!===========================================================================

    rff(1,IGlass) = Material(LayPtr)%ReflectSolBeamFront
    rbb(1,IGlass) = Material(LayPtr)%ReflectSolBeamBack
    rff(2,IGlass) = Material(LayPtr)%ReflectVisBeamFront
    rbb(2,IGlass) = Material(LayPtr)%ReflectVisBeamBack
  END IF
 END DO  ! End of loop over glass layers in the construction for front calculation

 ! Loop over incidence angle from 0 to 90 deg in 10 deg increments.
 ! Get glass layer properties, then glazing system properties (which include the
 ! effect of inter-reflection among glass layers) at each incidence angle.

 DO IPhi = 1,10
  Phi = FLOAT(IPhi-1)*10.
  CosPhi = COS(Phi*DegToRadians)
  if (abs(CosPhi) < .0001) CosPhi=0.0

  ! For each wavelength, get glass layer properties at this angle of incidence
  ! from properties at normal incidence
  DO IGlass = 1,NGlass
    DO ILam = 1,numpt(IGlass)

      ! ===========================================================================
      !      The following section is added by
      !      Mr. S.L. Wong and Mr. Ernest K.W. Tsang on 18th August 2006
      !      Modified on 12th September 2006
      !===========================================================================

           CALL TransAndReflAtPhi(CosPhi,t(ILam,IGlass),rff(ILam,IGlass),rbb(ILam,IGlass), &
                                  tPhi(ILam,IGlass),rfPhi(ILam,IGlass),rbPhi(ILam,IGlass))

           IF (solarfilm(IGlass)) then
                IF (ILam == 1) THEN
```

```
            tPhi(ILam,IGlass) = (0.0041*Phi+0.2447)*tPhi(ILam,IGlass)
          ELSE IF (ILam == 2) THEN
            tPhi(ILam,IGlass) = 0.3707
          END IF
        END IF
    ! ================================================================================

    END DO

    ! For use with between-glass shade/blind, save angular properties of isolated glass
    ! for case that all glass layers were input with spectral-average properties
    IF(AllGlassIsSpectralAverage) THEN
      tBareSolPhi(IPhi,IGlass)  = tPhi(1,IGlass)
      tBareVisPhi(IPhi,IGlass)  = tPhi(2,IGlass)
      rfBareSolPhi(IPhi,IGlass) = rfPhi(1,IGlass)
      rfBareVisPhi(IPhi,IGlass) = rfPhi(2,IGlass)
      rbBareSolPhi(IPhi,IGlass) = rbPhi(1,IGlass)
      rbBareVisPhi(IPhi,IGlass) = rbPhi(2,IGlass)
      afBareSolPhi(IPhi,IGlass) = MAX(0.0,1-(tBareSolPhi(IPhi,IGlass)+rfBareSolPhi(IPhi,IGlass)))
      abBareSolPhi(IPhi,IGlass) = MAX(0.0,1-(tBareSolPhi(IPhi,IGlass)+rbBareSolPhi(IPhi,IGlass)))
    END IF
  END DO

  ! For each wavelength in the solar spectrum, calculate system properties
  ! stPhi, srfPhi, srbPhi and saPhi at this angle of incidence.
  ! In the following the argument "1" indicates that spectral average solar values
  ! should be used for layers without spectral data.
  CALL SystemSpectralPropertiesAtPhi(1,NGlass,0.0,2.54)

  ! Get solar properties of system by integrating over solar irradiance spectrum.
  ! For now it is assumed that the exterior and interior irradiance spectra are the same.
  CALL SolarSprectrumAverage(stPhi, tsolPhi(IPhi))
  CALL SolarSprectrumAverage(srfPhi,rfsolPhi(IPhi))
  CALL SolarSprectrumAverage(srbPhi,rbsolPhi(IPhi))

  DO IGlass=1,NGlass
    DO ILam=1,nume
      sabsPhi(ILam) = saPhi(ILam,IGlass)
    END DO
    CALL SolarSprectrumAverage(sabsPhi,solabsPhi(IPhi,IGlass))
  END DO

  ! Get visible properties of system by integrating over solar irradiance
  ! spectrum weighted by photopic response.
  ! Need to redo the calculation of system spectral properties here only if
  ! one or more glass layers have no spectral data (lquasi = .TRUE.); in this
  ! case the spectral average visible properties will be used for the layers
  ! without spectral data, as indicated by the argument "2".

  if (lquasi) CALL SystemSpectralPropertiesAtPhi(2,NGlass,0.37,0.78)
  CALL VisibleSprectrumAverage(stPhi,  tvisPhi(IPhi))
  CALL VisibleSprectrumAverage(srfPhi, rfvisPhi(IPhi))
  CALL VisibleSprectrumAverage(srbPhi, rbvisPhi(IPhi))

END DO  ! End of loop over incidence angles for front calculation

IF(AllGlassIsSpectralAverage) THEN
  DO IGlass = 1,NGlass
    CALL W5LsqFit(CosPhiIndepVar,tBareSolPhi (:,IGlass),6,1,10,Construct(ConstrNum)%tBareSolCoef(IGlass,:))
    CALL W5LsqFit(CosPhiIndepVar,tBareVisPhi (:,IGlass),6,1,10,Construct(ConstrNum)%tBareVisCoef(IGlass,:))
    CALL W5LsqFit(CosPhiIndepVar,rfBareSolPhi(:,IGlass),6,1,10,Construct(ConstrNum)%rfBareSolCoef(IGlass,:))
    CALL W5LsqFit(CosPhiIndepVar,rfBareVisPhi(:,IGlass),6,1,10,Construct(ConstrNum)%rfBareVisCoef(IGlass,:))
    CALL W5LsqFit(CosPhiIndepVar,rbBareSolPhi(:,IGlass),6,1,10,Construct(ConstrNum)%rbBareSolCoef(IGlass,:))
    CALL W5LsqFit(CosPhiIndepVar,rbBareVisPhi(:,IGlass),6,1,10,Construct(ConstrNum)%rbBareVisCoef(IGlass,:))
    CALL W5LsqFit(CosPhiIndepVar,afBareSolPhi(:,IGlass),6,1,10,Construct(ConstrNum)%afBareSolCoef(IGlass,:))
    CALL W5LsqFit(CosPhiIndepVar,abBareSolPhi(:,IGlass),6,1,10,Construct(ConstrNum)%abBareSolCoef(IGlass,:))
  END DO
END IF

Construct(ConstrNum)%ReflectSolDiffFront = DiffuseAverage(rfsolPhi)
Construct(ConstrNum)%ReflectSolDiffBack  =  DiffuseAverage(rbsolPhi)
Construct(ConstrNum)%ReflectVisDiffFront = DiffuseAverage(rfvisPhi)
Construct(ConstrNum)%ReflectVisDiffBack  =  DiffuseAverage(rbvisPhi)
```

```
! ==========================================================================================
!     The followings are added by
!     Mr. S.L. Wong and Mr. Ernest K.W. Tsang on 12th September 2006
! ==========================================================================================

  WindowFilm     = .False.
  DO IGlass = 1,NGlass
       IF (solarfilm(IGlass)) THEN
              WindowFilm = .TRUE.
       END IF
  END DO
! ==========================================================================================

! ==========================================================================================
!     The followings are rewrited by
!     Mr. S.L. Wong and Mr. Ernest K.W. Tsang on 12th September 2006
! ==========================================================================================


  IF (WindowFilm) THEN
       tsolDiff = .2
       tvisDiff = .3664
  ELSE
       tsolDiff = DiffuseAverage(tsolPhi)
       tvisDiff = DiffuseAverage(tvisPhi)
  END IF
```

Appendix III – Selected Publications

Journal Papers

1. Li, DHW, Lam, JC and Wong, SL (2002) Daylighting and Implication to Overall Thermal Transfer Value (OTTV) Determination, Energy, 27(11), 991-1008.

2. Li, DHW, Wong, SL and Lam, JC (2003) Climatic Effects on Cooling Load Determination in Subtropical Regions, Energy Conversion & Management, 44(11), 1831-1843.

3. Li, DHW, Lam, JC and Wong, SL (2005) Daylighting and Its Effects on Peak Load Determination, Energy, 30(10), 1817-1831.

4. Li, DHW, Lam, TNT and Wong, SL (2006) Lighting and Energy Performance for an Office Using High Frequency Dimming Controls, Energy Conversion & Management, 47(9-10), 1133-1145.

5. Li, DHW, Wong, SL, Tsang, CL and Cheung, GHW (2006) A Study of the Daylighting Performance and Energy Use in Heavily Obstructed Residential Buildings via Computer Simulation Techniques, Energy and Buildings, 38(11), 1343-1348.

6. Li, DHW, Tsang, EKW, Lam, TNT, and Wong, SL (2007) A Simple Software Tool for Determining Internal Daylight Illuminance, Journal of Harbin Institute of Technology, 14, Supp., 306-309. The 4th International Workshop on Energy and Environment of Residential Buildings, Harbin, China, 15-16 January, 2007.

7. Li, DHW and Wong, SL (2007) Daylighting and Energy Implications due to Shading Effects from Nearby Buildings, Applied Energy, 84(12), 1199-1209.

8. Li, DHW, Lam, TNT, Wong, SL and Tsang, EKW (2008) Lighting and Cooling Energy Consumption in an Open Plan Office using Solar Film Coating", Energy,

33(8), 1288-1297.

9. Li, DHW, Wong, SL and Cheung, KL (2008) Energy Performance Regression Models for Office Buildings with Daylighting Controls, Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy. (Accepted but not yet published)

Conference Papers

1. Li, DHW, Lam, JC and Wong, SL (2001) Analysis of Solar Heat Gain Factors and Design Implications for Hong Kong, In Proceedings of the 4th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings, Cheung Sha, Hunan, China, 2, 1203-1210.

2. Li, DHW, Lau, CCS, Wong, SL and Lam JC (2003) Sky Radiance Distribution and Its Implications to Building-Integrated Photovoltaic (BIPV) Designs, In Proceeding of the 3rd China Urban Housing Conference, Hong Kong, 359-366.

3. Li, DHW, Wong, SL, Tsang, CL and Cheung, GHW (2004) A Study of the Daylighting Performance in Heavily Obstructed Residential Buildings via Computer Simulation Techniques, In Proceeding of the 3rd International Workshop on Energy and Environment of Residential Buildings, Xi'an, China, 144-149.

4. Li, DHW, Wong, SL and Lam, TNT (2005) Lighting Energy Use under Daylight Linked Lighting Controls in Office Building, In Proceeding of the 2nd Joint Conference of SOLARIS 2005, Greece, Athens, 64-68.

5. Li, DHW, Wong, SL and Tsang, EKW (2006) LEA28-Overall Thermal Transfer Value (OTTV) Performance and Its Energy Implications on Public Housing in Hong Kong, In CD-ROM of the World Renewable Energy Congress IX. Florence, Italy.

6. Li, DHW, Wong, SL and Lam, JC (2007) Development of a Typical Meteorological Year for Building Energy and Daylighting Analysis in Hong

Kong, In Proceedings of the 3^{rd} International Conference of SOLARIS, Delhi, India, 1, 121-129.

7. Li, DHW, Tang, HL, Wong, SL, Tsang, EKW, Cheung, GHW, and Lam, TNT (2007) Skies Classification Using Artificial Neural Networks (ANN) Techniques, In Proceedings of the 6^{th} International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings, Sendai, Japan, 1, 61-68.

8. Li, DHW, Wong, SL and Mak, AHL (2008) A Case Study of Energy Performance for Solar Control Coating in an Air-conditioned Commercial Building, In Proceedings of the First International Conference on Building Energy and Environment, Dalian, China, 183-190.

9. Li, DHW, Cheung, KL, Wong, SL and Lam, TNT (2008) A Study of Solar Irradiance on Inclined Surfaces and Design Implications, In Proceedings of the First International Conference on Building Energy and Environment, Dalian, China, 531-539.