SOMFY - PHILIPS Light balancing Whitepaper

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Table of Contents

1.   Introduction

One of the fundamental requirements of buildings is to provide a sheltered living and working space from the extremes of climate. The objective of environmental building design is to create a comfortable yet energy efficient internal environment. Consequently, building façade becomes the actual separator between the indoor and outdoor climate and has a filtering effect on the external impacts. The general performance requirement for building façade varies with location and climate, building type and interior spatial design as well as the needs determined by interior visual tasks. These often interrelate in an intricate way and are time dependent. Therefore, choosing an optimal façade is a complex discipline with many often contradictory parameters of considerable interdependence (Ochoa and Capeluto, 2009). For example, maximization of daylight usage is desired as it reduces electricity consumption for lighting and enhances visual quality. Nevertheless, large fenestration areas often results in excessive solar gains and high varying heating and cooling loads as well as glare problems. As a result, introduction of dynamic fenestration whose optical behaviour (transmission, refection and scattering) may change over time due to shading devices may create the possibility of obtaining a more beneficial utilisation of the available resources, such as insolation and daylight, with respect to both energy demand requirement and occupant comfort (Lee, et al. 1998). Moreover, driven by technological advances in transparent building facades, design alternatives have shifted to utilizing dynamic fenestration and shading systems for optimal control of daylighting and solar gains (Athanassios and Andress, 2006).

Building façade can be constructed with a number of static and dynamic components that in combination are capable of preventing thermal and visual discomfort. Shading should be considered as an integral part of fenestration system design in order to balance daylighting requirements versus the need to reduce solar gains. Recent studies (Tzempelikos and Sthienitis, 2003; Johnson et al. 1984) have shown that appropriate shading design and control, when linked with simultaneous control of electric lighting and HVAC components, could significantly reduce peak cooling load and electricity consumption while maintaining good thermal and illuminance indoor conditions. This is particularly important for being able to achieve nearly-zero energy buildings from 2018-2020 as required by the recent 2010 Energy Performance of Building Directive (EPBD 2010). It has been recognised that the trend for energy consumption in buildings is a decrease of thermal energy for space conditioning and an increase of electricity for installations and appliances (Bloem and Atanasiu, 2009). Electric lighting is one area where energy savings are possible at reasonable cost in new buildings as well as in retrofit projects. Therefore there is a significant opportunity for potential energy reductions and increase in occupant comfort through implementing integrated lighting and shading controls. However, this is only possible by carefully selecting fenestration and shading properties and control, taking into account their combined impact and then optimizing their operation (Athanassios and Andress, 2006). If the fenestration systems impose adverse thermal loads, the actual savings from the use of daylight to replace or supplement electric lighting may be reduced. The key issue is to accurately evaluate the performance of integrated dynamic façades in terms of their detailed optical and thermal characterization. The most effective means of achieving this is through detailed, dynamic, hourly or sub-hourly computer simulations that model thermal and daylighting performance in an integrated manner to determine the level of indoor environment and the energy demand for heating, cooling and artificial lighting.

In this paper, the focus is on quantifying potential energy savings from employing various shading and lighting controls in buildings and investigating the integrated impact on heating, cooling and lighting energy demands by using IES <VE>, the advanced building performance simulation tool. A case study was carried out based on Somfy - Philips shading and lighting control system, called 'light balancing'. A range of shading controls comprising both manual and automated blind controls and a set of lighting controls including manual, occupancy-sensing and dimming controls were explored respectively based on an office building model for 5 different climatic locations. Comparisons of energy performance between these controls were examined. Based on simulation results, it has been indicated that by introducing shading and lighting controls it generally reduces the total energy consumption and the overall energy saving can be achieved up to 8% compared to

a baseline scenario where there was no blind installed and the lighting was simply manually operated. It is worth mentioning that the predicted energy saving was only an indication based on the setup of the case study and the energy saving can be genuinely increased if a better blind fabric is chosen, a better floor layout is designed or different control thresholds are selected. It is also noted that the type of control strategy and the local climatic condition play a key role in determining the extent to which the energy consumption can be reduced. As expected, the time based switching blind control and the occupancy based light switching & daylight dimming control have individually proved to be the most energy efficient approach amongst the investigated shading control strategies and the lighting control strategies respectively.

2.   Somfy - Philips Light Balancing System

Somfy - Philips 'light balancing' system (Somfy website) is a dynamic solar shading and lighting control system, which reacts by taking into account the occupant presence and external climatic conditions in order to achieve visual comfort when a space is occupied and energy saving when the space is vacant. In general, visual comfort is the key if the space is occupied. In this sense, solar shading will be positioned automatically to avoid glare but still allowing natural daylighting while the luminaire photo sensor dims the light. However occupants are able to override the system and control the position of the solar shading manually via their RTS remote control. The lighting system will adjust the level of light automatically based on the incoming daylight level. If the space is vacant, the luminaires are turned off and the solar shading will be either completely open or closed depending on the heating and cooling needs as well as the external climatic conditions. Figure 2-1 illustrates the light balancing mechanism in different scenarios.

External climatic condition: no sun (no direct solar radiation, cloudy (diffuse solar radiation available)
Occupancy: yes
Internal natural light: low and need artificial lighting
Artificial light: maximum

External climatic condition: a little sun, some clouds
Occupancy: yes
Internal natural light: maximum, prevent glare
Artificial light: medium
Priority: visual comfort

External climatic condition: sunny
Occupancy: yes
Internal natural light: maximum, no direct glare
Artificial light: minimum
Priority: visual comfort

External climatic condition: warm period
Occupancy: no
Priority: prevent cooling

External climatic condition: cool period
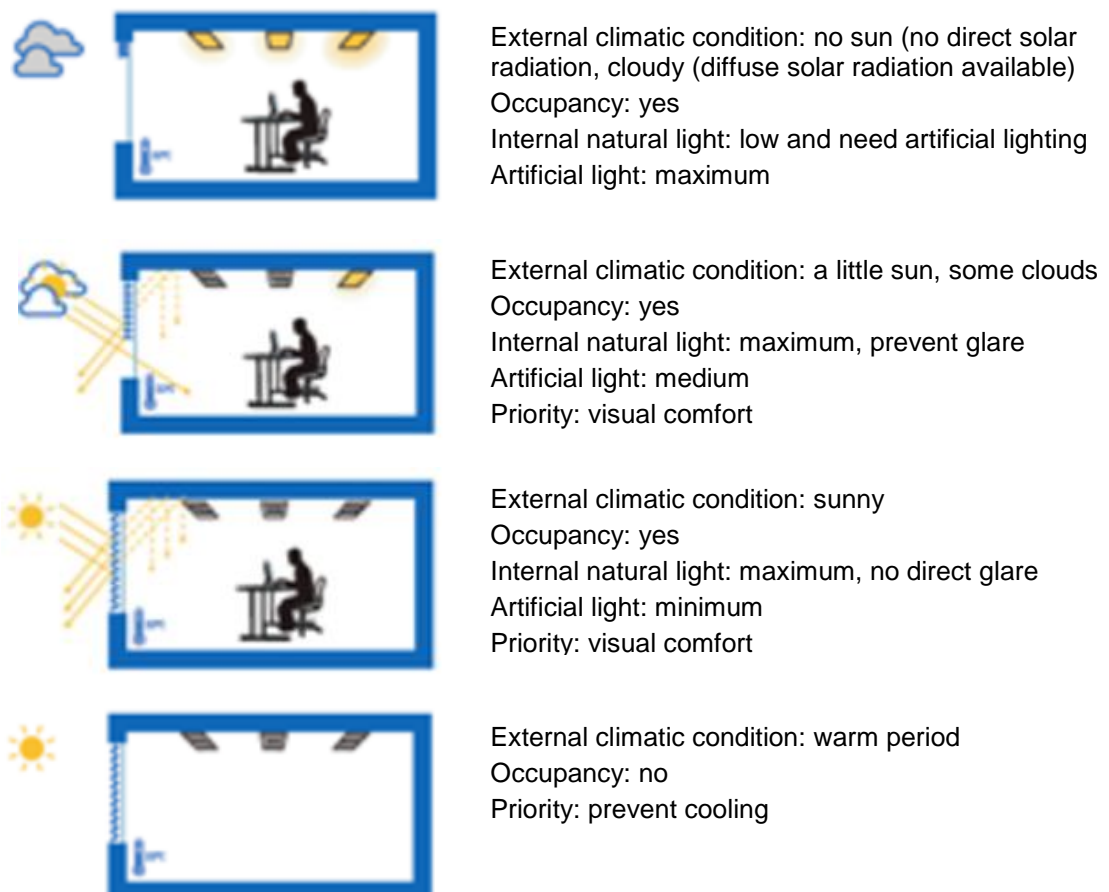Occupancy: no
Priority: prevent heating

Figure 2-1: Illustration of SOMFY - PHILIPS light balancing (SOMFY 2012)

In order to better understand the 'light balancing' dynamic shading and lighting control system and to explore its potential benefit on the heating, cooling and lighting energy demands, this paper sets out to examine various shading and lighting controls from basic manual mode to advanced automated mode with a certain assumptions and simplification using dynamic simulation modelling method. The simulated energy performances are then compared with intent to gain the knowledge of their potential impacts and benefits.

3.   Shading and lighting control algorithms

In this section, the examined shading and lighting control algorithms are presented in details, which were provided by Somfy and Philips. Only the internal blinds are considered in this study.

3.1 Shading control algorithms

Static manual blind control

In this manual control mode, the internal blind is completely lowered during the occupied period and is fully retracted during the un-occupied period. This can be seen as a simple on and off control strategy according to the occupancy schedule used in each space. For example, offices are occupied from 08:00 to 17:00 in weekdays and are completely un-occupied in weekend, therefore the static manual blind control for office spaces would be the blind is fully lowered from 08:00 to 17:00 and is retracted during the period of 18:00-24:00 and 00:00-07:00 in weekdays and in weekend the blind is fully retracted. Note that different space types may have different occupancy profiles; therefore the static manual blind control may differ accordingly.

In practice, this type of blind control is often applied to interior roller blinds; therefore a normal roller fabric has been used for simulating the control strategy here. Details of the fabric's thermal performance refer to Appendix A.

Dynamic manual blind control

In this control mode, the blind is manually operated by the occupants based on the internal illuminance level of a space. When the space is occupied and its internal illuminance level reaches 5000lux, the blind is fully lowered by the occupant. Once the blind is lowered, it remains the lowered position for the whole day and will be raised up the next day upon occupant first arrival. In this sense, the blind position during the weekend will be dependent on whether it's open or closed on previous Friday. Hence, settings of the dynamic manual blind control will differ due to different occupancy schedules (the start time) and the internal illuminance level. An interior venetian blind has been applied to this control and details see Appendix A.

Automated time-based blind control

This is an automated control mode. The blind is automatically controlled according to external illuminance level and occupancy schedule as well as the space heating and cooling needs. There are two control modes dependent on the difference between weekday and weekend and occupied and un-occupied conditions. During weekdays in occupied period, the blind control is in comfort

mode; otherwise, it is in eco mode. Note that the time-based control is occupancy related and it is not timer-based.

Comfort mode

The blind is lowered completely as soon as the external illuminance is equal to or above 15000lux. The blind is retracted otherwise.

Eco mode

- During daytime, the blind is retracted, when
  - The external illuminance at the window is above 15000lux
  - The building has a need for heating (zone temperature < heating set point)

- During daytime the blind is lowered, when
  - The external illuminance at the window is above 15000lux
  - The building has a need for cooling (zone temperature > cooling set point),

- During nighttime the sun blind is lowered when
  - The external illuminance at the window is below 15000lux
  - The building has a need for heating (zone temperature < heating set point)

- During nighttime the blind is retracted when
  - The external illuminance at window is below 15000lux
  - The building has a need for cooling (zone temperature > cooling set point)

The same type of interior venetian blind, as described in Appendix A, has been applied to this control. The venetian blind was assumed to be either fully open or fully closed, therefore the angle of the venetian blind is not considered in this study.

3.2 Lighting control algorithms

Manual lighting control

The manual lighting control is the most common practice and also is the most un-predictive operation as it is largely determined by the individual preference and by whether a space is actually occupied or un-occupied. It is generally regarded as the most energy intensive lighting approach and tends to be oversimplified, e.g. the lighting is 100% on during the whole working hours. In this study, an optimistic assumption of the manual lighting control has been adopted to illustrate a scenario which is not extremely energy intensive. As a result, it has been assumed that in weekdays lights are on at 90% during the occupied period and at 5% during un-occupied period. In weekends lights are off.

Occupancy based switching lighting control

This is an automated switching control based on the sensed occupancy status. It has been assumed that for perimeter zones lights are automatically switched on if occupants are present and off if no one is present with a 15min time out setting. For core zones lights are turned on during the occupied period and turned to 10% during the un-occupied period. The time out setting is to prevent the lights from constantly changing between on and off states in response to short transient conditions. Note that the perimeter zone is defined as a space which has external glazing and vice versa for the core zone. Figure 3-1 compares the manual lighting control with the occupancy based switching control based on office spaces for weekdays.

Occupancy based switching & daylight dimming control

This control implements not only the occupancy based switching as described above, but also adds dimming due to available daylight. The dimming control is operated according to the external illuminance level and the dimming threshold is set as 650 lux. Lights are ideally linearly dimmable from 100% to 0% when the sensed external illuminance level varies from 0 lux to 650 lux. This is considered to be the most energy efficient approach amongst the three lighting options.

Note that the occupancy information is shared between the Somfy and Philips Lighting system.
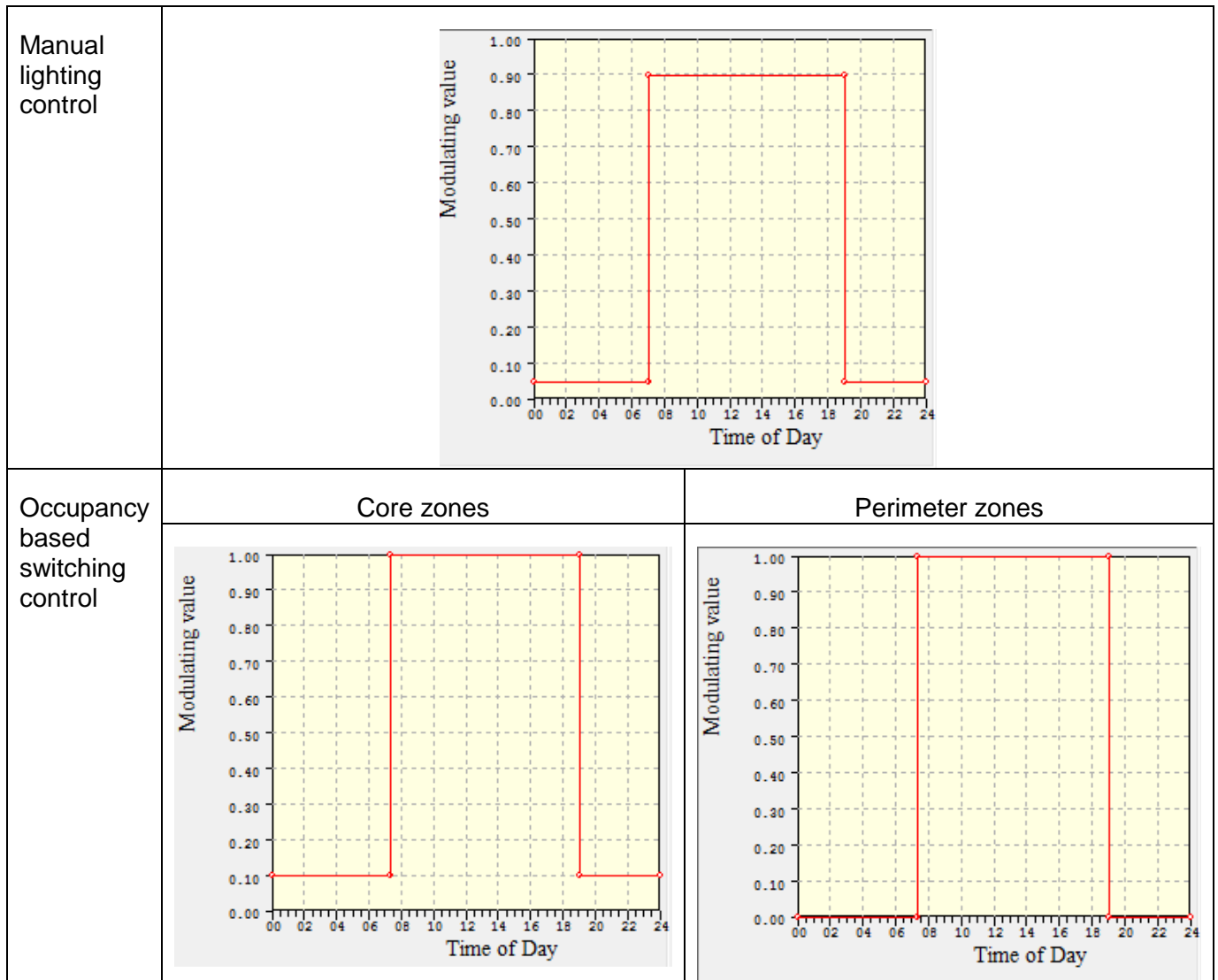
Manual lighting control		
Occupancy based switching control	Core zones	Perimeter zones

Figure 3-1 Comparison between manual lighting control and occupancy based switching control for office spaces in weekdays

4.   Methodology

Dynamic computer simulation is used to quantify the impact of various shading and lighting controls on the heating, cooling and lighting energy demands and to assess the potential energy savings from the employment of the integrated dynamic shading and lighting control approach based on an office building model. This section details methods used for delivering such simulation modelling.

4.1 Climatic Locations

Climatic condition plays an important role in the design and control of a shading system and has an impact on both daylighting and thermal performance of buildings. In order to have a full picture of the climatic effect within this study, five locations have been selected to represent some of the most typical climate zones in the world, which are:

Singapore: representing tropical/megathermal climates, known for their high temperatures year round and for their large amount of year round rain.

UAE Abu Dhabi: representing dry (arid and semiarid) climates, characterized by little rain and a huge daily temperature range.

Paris: representing maritime temperate climates or oceanic climate, known for that summers are cool due to cool ocean currents, but winters are milder than other climates in similar latitudes but usually very cloudy.

San Francisco: representing dry-summer subtropical or Mediterranean climates, known for summers that are hot and dry, due to the domination of the subtropical high pressure systems, except in the immediate coastal areas, where summers are milder due to the nearby presence of cold ocean currents that may bring fog but prevent rain.

Beijing: representing continental/micro-thermal climate, characterised by hot, humid summers and generally cold, windy, dry winters.

Weather data used for the five locations are standard hourly weather files, which are IWEC format for Singapore, UAE Abu Dhabi, Beijing and Paris and TMY2 format for San Francisco. IWEC (International Weather for Energy Calculations) data files are suitable for use with building energy simulation programs for 227 locations outside the USA and Canada and TMY2 (Typical Meteorological Year 2) data sets are intended to use for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories (Energy plus website). Both weather data formats represent typical weather conditions. Figure 4-1 compares hourly dry-bulb temperatures of the five climatic locations in general and Figure 4-2 shows detailed breakdown of hours over a series of temperature ranges in steps of every 5 ^{o}C for each location. It can be seen that Abu Dhabi has the hottest summer over the five locations. The dry-bulb temperature can reach over 40 ^{o}C and there are total 1515 hours in which the temperature is above 35 ^{o}C. However, the temperature is seen to drop down from November to March around 12 ^{o}C to 25 ^{o}C. Singapore also has a hot weather, but it doesn't seem to have clear-cut seasons as the temperature is quite uniform all year round. There are 6514 hours in which the air temperature remains between 25 ^{o}C and 30 ^{o}C. In contrast, both Beijing and Paris have a wider temperature range, varying from -5 ^{o}C to 35 ^{o}C. Compared with Paris, Beijing has a hotter summer and a colder winter. Among the five locations, San Francisco seems to have a cool to mild weather throughout the year. There are 4482 hours that the dry-bulb temperature is around 10-15 ^{o}C and only 163 hours that the temperature drops to 0-5 ^{o}C.
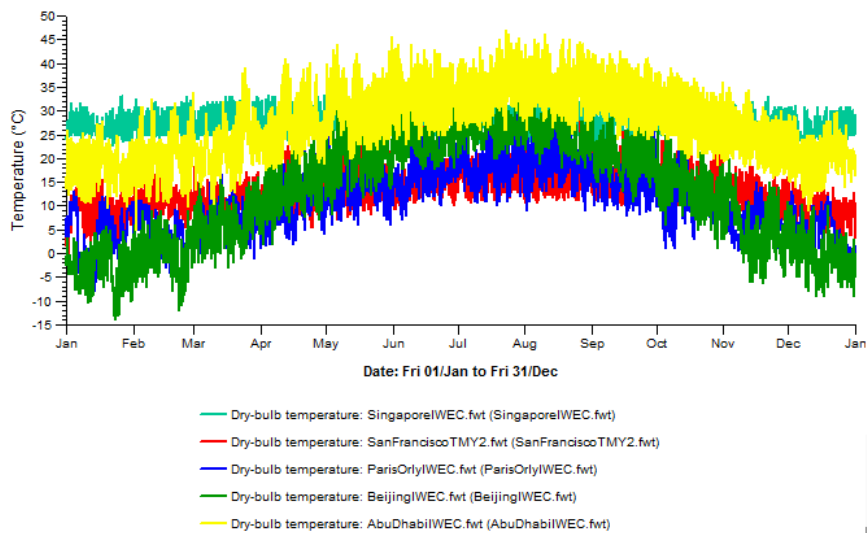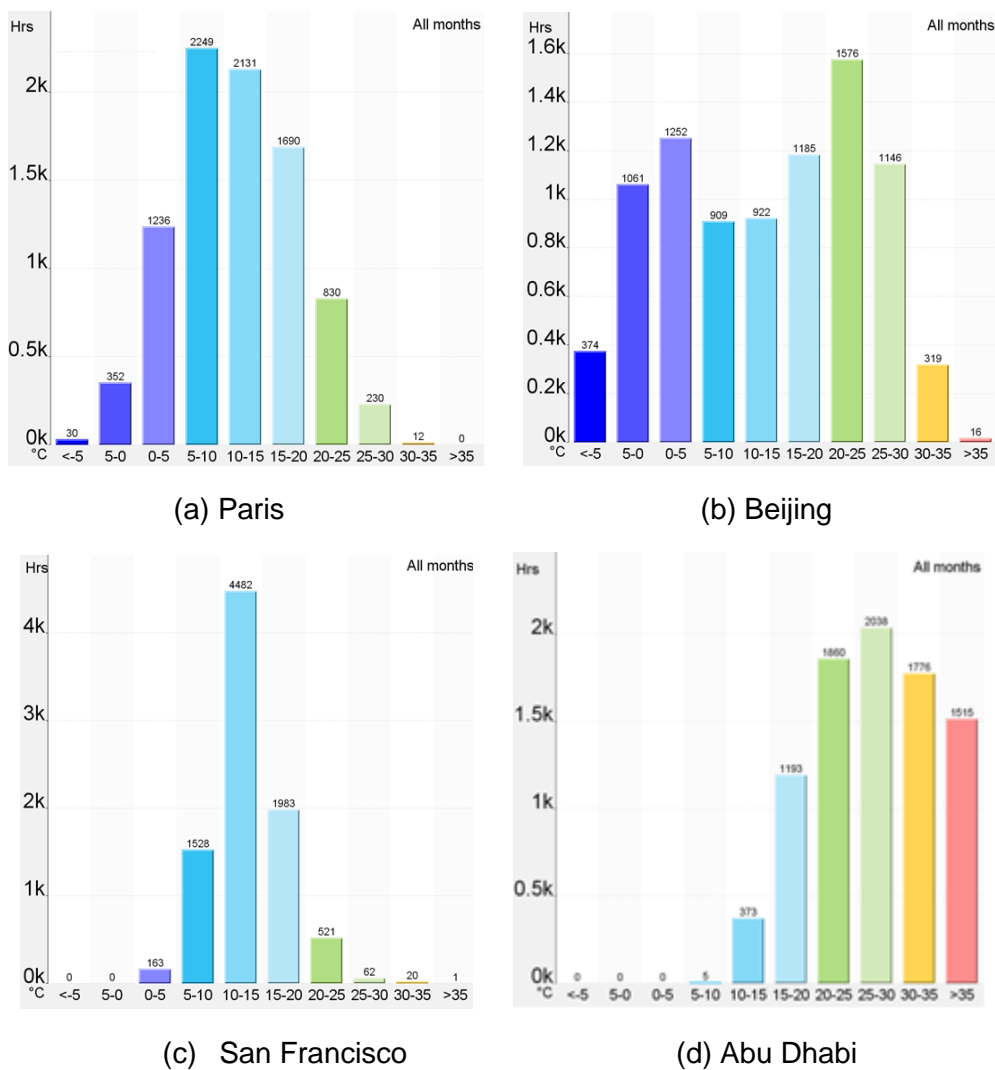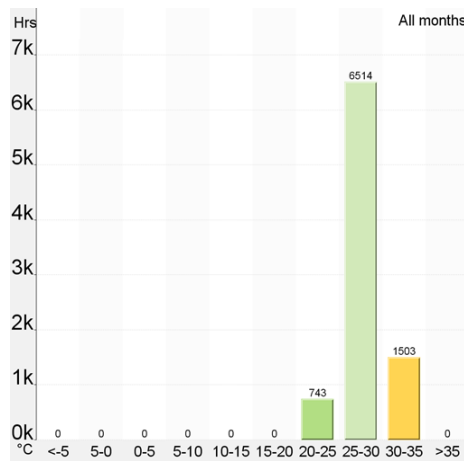
Figure 4-1 Comparison of dry-bulb temperature between the five climatic locations

(a) Paris

(b) Beijing

(c) San Francisco

(d) Abu Dhabi

(e) Singapore

Figure 4-2 Breakdown of hours over a series of temperature arranges for the five locations

Figures 4-3 and 4-4 show the maximum and mean global radiation, direct radiation and diffuse radiation respectively between the five climatic locations. Note that for the same climatic location, the maximum global radiation, the maximum direct radiation and the maximum diffuse radiation do not necessarily appear at the same time/date, therefore the sum of the maximum direct radiation and diffuse radiation is not equal to the maximum global radiation.

As indicated in the two graphs, Abu Dhabi has the highest solar radiation level in terms of the maximum and the mean values while Paris has the lowest solar radiation level. Singapore also has rather high solar radiations. It is also noted that although San Francisco has a mild weather condition, it actually has a good solar resource. The maximum and mean direct solar radiation can reach 900 W/m^2 and 172W/m^2 respectively.
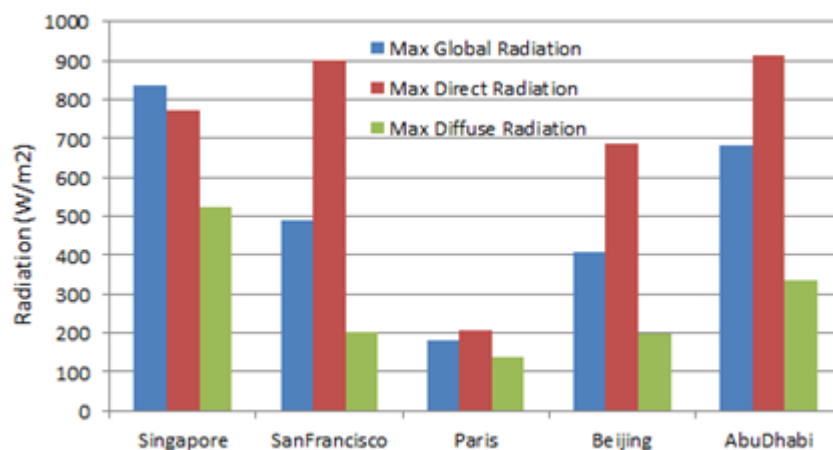

Figure 4-3 Comparisons of maximum global, direct and diffuse radiations between the five climatic locations
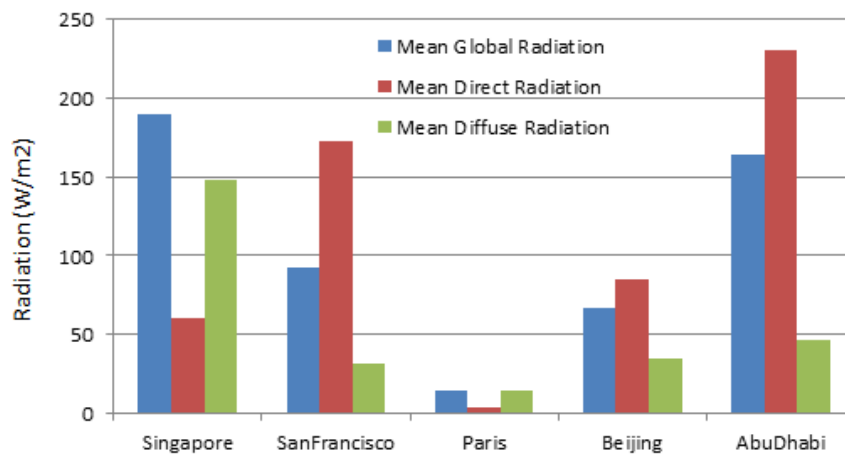
Figure 4-4 Comparisons of mean global, direct and diffuse radiations between the five climatic locations

4.2 Office Building Model

The case study building was intended to be representative as well as to allow the impact of various shading and lighting controls to be assessed correctly. It is believed that commercial buildings and primarily office buildings are classified among the building presenting the highest energy consumption (Marie and Ake, 2011). The total annual energy use in office buildings varies in the range 100-1000 kWh/m^2 ·yr, depending on the geographic location, use and type of office equipment, operational schedules, type of envelope, use of HVAC systems, type of lighting, etc. (Marie and Ake, 2011). Therefore, the building model was created as a seven storey office building as shown in Figure 4-5.

The office building has multi-thermal zones comprising open plan and cellular office spaces, circulation area, gym, storage, toilet, kitchen, waiting area, café and changing room. There are 245 zones in total, of which 61 zones are perimeter spaces, 141 zones are core spaces and 43 zones represent ceiling voids. The total floor area of the building was 31609.51 m^2. The total building height was 46m and the floor-to-floor height was 4m. The window to wall ratios of the building model are summarised as below:

- East façade window to wall ratio = 0.399

- West façade window to wall ratio = 0.491

- South Façade window to wall ratio = 0.785

- North Façade window to wall ratio = 0.8194

- Overall façade window to wall ratio = 1.137

Plan views of the building model are shown in Appendix B. Constructions of the office building are also summarised in Appendix B.
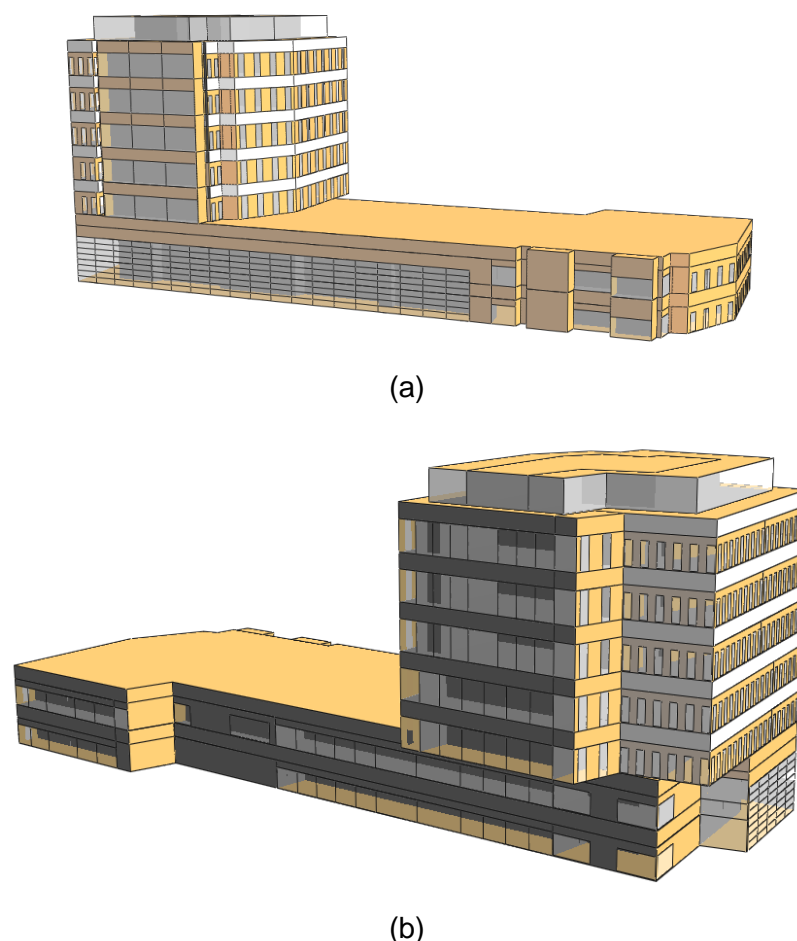
(a)

(b)

Figure 4-5 Axonometric of the office building model

To represent a typical internal gain from lighting, equipment and occupancy of an office, settings of the building model need to be standard and representative. Therefore, it was decided to follow the standard data sets from the UK NCM (National Calculation Methodology) Modelling Guide. The NCM Modelling Guide defines the procedures for demonstrating compliance with the Building Regulations for buildings other than dwellings under the European Energy Performance of Buildings Directive (EPBD). In order to facilitate estimating energy performance on a consistent basis, a key part of the NCM is a set of databases that define the activities in various types of space in different classes of building. The database provides standard occupancy patterns, temperature set-points, outdoor air rates and heat gain profiles for each type of space in the buildings, so that buildings with the same mix of activities will differ only in terms of their geometry, construction, building services and weather location. The lighting, equipment and occupancy gains associated with the different zones of the office building are listed in Appendix B.

It should be noted that, except for the lighting schedule, both equipment and occupancy profiles were directly taken from the NCM Modelling Guide. Occupancy schedules are fixed profiles which were defined based on space types. In addition, the lighting is calculated based on lighting gains in unit of W/m^2 and the lighting schedule profiles. The lighting gain is a standard figure which varies with the space type. Hence, there are no specific lighting types associated.

The office building model was mainly conditioned by a Fan Coil Unit system except for circulation area, toilets, kitchens, changing rooms and storage. Details of all the HVAC systems applied to the building model and their associated heating/cooling set points and ventilation rates are listed in Appendix B.

4.3   Simulation modelling

The impact of introducing a range of solar shading and lighting controls on the building energy performance across different climates were investigated by using dynamic computational simulations. A state-of-the-art energy modelling tool, IES <VE> was employed to carry out the investigation. The IES <VE> is a suite of building performance modelling tools based around a single integrated data model. It is comprised of a series of individual modules including climate, geometric modelling, solar shading, energy and carbon, lighting, airflow, value/cost and egress modules but linked by a Common User Interface (CUI) and a single Integrated Data Model (IDM), which allows data input being passed among different applications.

As described in the previous section, both solar shading and lighting controls are based on internal or external illuminance level, which requires an integrated modelling approach for analysis. The simulation work can be divided into two parts; first, the evaluation of dynamic daylight availability inside or outside each perimeter room and secondly the implementation of the solar shading and lighting control systems. These were modelled by using the <VE> lighting module, Radiance IES, and the energy and carbon module, ApacheSim respectively. Radiance is a software package developed by the Lighting Systems Research group at the Lawrence Berkeley Laboratory, U.S. It has been integrated into the <VE> and is compatible with other modules. It is used for calculating lighting levels (LUX), Daylight Factors or Glare for daylight and/or artificial lighting. ApacheSim is a dynamic thermal simulation module based on first-principles mathematical modelling of the heat transfer processes occurring in and around a building, which meets ASHRAE Standard 140. Within it, conduction, convection and radiation heat transfer processes for each element of the building fabric are individually modelled and integrated with models of room heat gains, air exchanges and HVAC plant operation.

The thermal simulation was conducted in conjunction with the daylight simulation for modelling, the shading and lighting control strategies. Radiance IES calculates illuminances for a standard overcast sky and a number of clear skies with different sun positions. At the coincident simulation time ApacheSim mixes these skies in appropriate amounts to match the weather conditions at each hour of the simulation. This involves applying luminous efficacies to the weather file solar variables (W/m^2) to generate illuminance values (lux), from which multipliers are obtained scaling the contributions of the standard overcast and clear skies. There are three sky components in general; one overcast sky and two clear skies with different sun positions which are combined using interpolation. The multipliers are then applied to the internal sensor illuminances calculated by Radiance IES for the standard skies to derive the internal sensor illuminances for the hour in question.

To take full advantage of available daylight and avoid dark zones, lighting zoning has been applied to perimeters zones, which virtually not physically divides a perimeter zone 6m from an external wall containing 15% glazing or more. There was one sensor positioned 2.23 m along the centreline from the window in the front zone at a height of 0.85m and one sensor positioned in the centre of the space in the back zone at the same height to calculate the horizontal internal illuminance levels which were then compared with the daylight dimming threshold (650 lux) to determine whether the artificial lighting would be dimmed. In addition, there were four sensors facing upward positioned horizontally 90 degree angle in between above the higher part of the roof to calculate the external illuminance level which was then used for the time based blind switching control.

There are a total of 7 simulation scenarios which were conducted individually for the 5 climatic locations, as detailed in Table 4-1:

Table 4-1 Summary of simulation scenarios

Scenario no	Shading control	Lighting control
1	No shading devices	Manual lighting
2	Static manual blind control	Manual lighting
3	Dynamic manual blind control	Manual lighting
4	Automated time-based blind control	Manual lighting
5	No shading devices	Occupancy based switching control
6	No shading devices	Occupancy based switching & daylight dimming control
7	Automated time-based blind control	Occupancy based switching & daylight dimming control

Note that:

- Scenario 1 is the **baseline model** which was used as the reference case to measure the potential energy savings that could be achieved by applying various shading and lighting controls;

- Scenarios 2-4 focused on investigating the shading controls; therefore the lighting control was simply set up as the manual control which means that the artificial lighting was operated in the same manner disregarding the availability of natural light;

- Scenario 5-6 focused on investigating the lighting controls, therefore the shading devices were not considered;

- Scenario 7 is referred as the **integrated dynamic shading and lighting control**, which was modelled as a combination of two separate controls, namely automated time-based blind control and occupancy based switching & daylight dimming control. In this sense, it hasn't been modelled in a real integrated manner.

5. Results and discussion

5.3 Shading control analysis

5.1.1 Baseline model (scenario 1)

Figures 5-1 to 5-4 show the room cooling plant sensible load, room heating plant sensible load, lighting energy and the total energy consumption of the baseline models for the five selected climatic locations respectively. The sensible load (either heating or cooling) is a measurement of amount of heat exchange in a unit time which has its sole effect of a change of temperature. The room heating/cooling plant sensible load is the sum of each room's heating/cooling sensible load in the building model. Note that the total energy consumption is not equal to the sum of the room cooling plant sensible load, the room heating plant sensible load and the lighting energy as it includes other types of energy consumptions e.g. equipment energy consumption.

As shown in Figure 5-1, Abu Dhabi and Singapore have much higher room cooling sensible loads than the other locations. This is due to their overall rather high dry-bulb temperatures and solar radiations. Especially for Abu Dhabi, it has the hottest summer over the five locations and nearly over one-sixth of the whole year the dry-bulb temperature is above 35 $^{\circ}$C, therefore it has the

highest cooling sensible load. On the other hand, there is no heating demand for Abu Dhabi and Singapore, as indicated in Figure 5-2. It is worth mentioning that the dry-bulb temperature in Abu Dhabi does drop down around 10-25 ^{o}C between November and March (see Figure 4-2), however due to the incoming solar gains and internal gains from lighting, occupancy and equipment, the room air temperatures of the office building model were above the heating set points.

It is also noted that overall San Francisco has very low cooling sensible load, heating sensible load and the total energy consumption. This results from its cool and mild weather condition throughout the entire year. In contrast, both Beijing and Paris have a wide temperature variation over the year. Compared with Paris, Beijing has a hotter summer and a colder winter. Therefore, both locations have considerable amount of sensible cooling and heating loads but Beijing consumed more energy than Paris.

In addition, as shown in Figure 5-3, the lighting energy consumption was the same for all the five locations as the same manual lighting control was applied. As a result, the artificial lighting was operated in the same manner and the availability of natural light due to different climatic locations was not considered in this case. Overall, it can be seen from Figure 5-4 that the total energy consumption varied from 2500 MWh to 3670 MWh due to the impact of the various climatic conditions. Abu Dhabi and Singapore have become the largest two energy consumers whilst San Francisco was the least energy consumer.
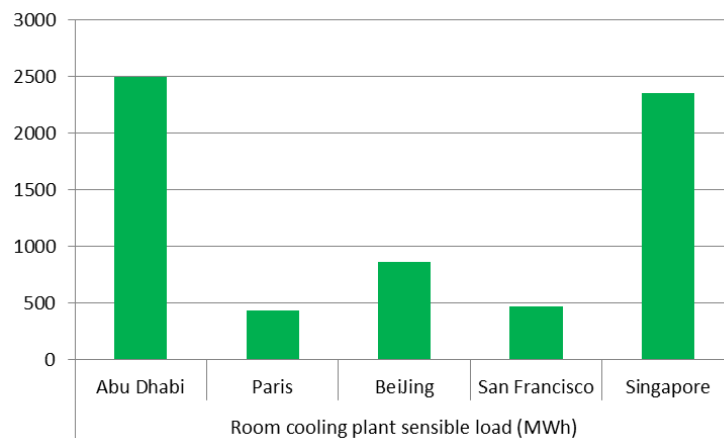

Figure 5-1 Cooling loads of baseline models for the five selected climatic locations
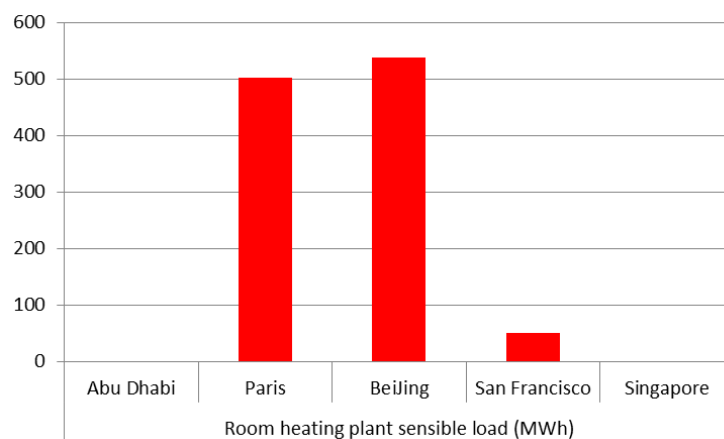

Figure 5-2 Heating loads of baseline models for the five selected climatic locations
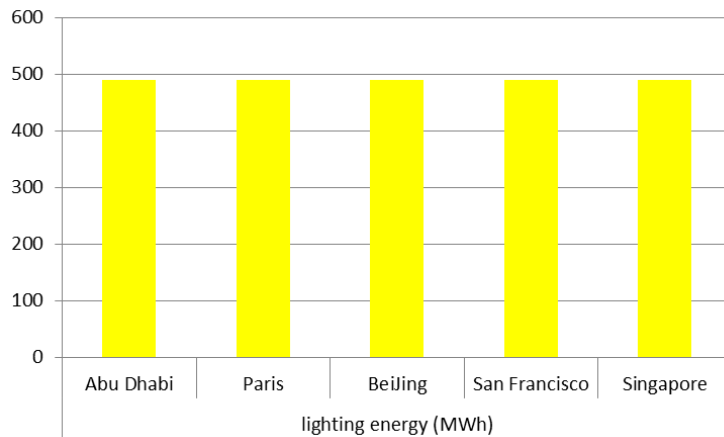
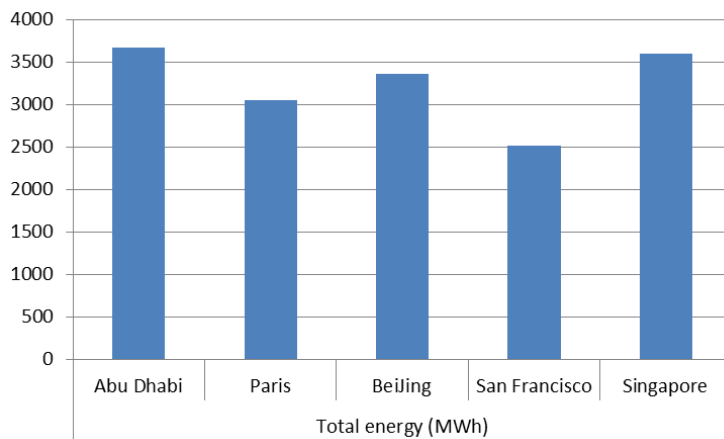Figure 5-3 Lighting energy consumptions of the baseline model for the five selected climatic locations

Figure 5-4 Total energy consumptions of baseline models for the five selected climatic locations

5.1.2 Static manual blind control (scenario 2)

Table 5-1 and Table 5-2 summary the room cooling plant sensible load, room heating plant sensible load, lighting energy and the total energy consumption between the baseline model (scenario 1), static manual blind control (scenario 2), dynamic manual blind control (scenario 3), automated time based blind control (scenario 4) and the integrated dynamic shading & lighting control (scenario 7) for the five locations with different units. Table 5-3 presents the corresponding percentage changes between these various blind controls and the baseline model. The static manual control was applied to the internal roller blinds to simulate the simplest operation scenario where occupants rarely operate the blinds during the occupied period; therefore the roller blinds will only be lowered during the occupied period and retracted during the un-occupied period. In order to examine whether the execution of the static manual control is accurate, comparison of solar gains with and without the blind control with reference to the occupancy schedule in a summer day are illustrated in Figure 5-5 based on open plan office 03, as shown in Figure 5-6.As expected, it can be seen that the roller blind has been in position within the occupied period as the solar gains have been reduced accordingly. The impact of the roller blind on the solar gains is clear. This has also been demonstrated in Figure 5-7, which shows the annual solar gains with and without the static manual control based on the open plan office 03.

Table 5-1 Summary of heating, cooling, lighting and total energy consumptions between various shading control strategies

Variables	Simulation scenarios	Abu Dhabi	Paris	Beijing	San Francisco	Singapore
Room cooling plant sensible load (MWh)	Baseline model (scenario1)	2491.9912	426.1197	856.1053	467.7997	2351.6121
	Static manual control (scenario 2)	2420.1514	362.3113	773.1715	370.2096	2195.7925
	Dynamic manual control (scenario3)	2422.8804	397.7576	822.0033	421.7047	2292.5061
	Automated time based control (scenario4)	2301.3967	351.1606	759.9544	356.134	2166.804
	Integrated dynamic shading & lighting (scenario7)	2217.397	303.8076	706.0468	295.1306	2071.7856
Room heating plant sensible load (MWh)	Baseline model (scenario1)	0	501.4344	538.1972	49.8319	0
	Static manual control (scenario2)	0	528.8313	581.3671	68.8183	0
	Dynamic manual control (scenario3)	0.0018	518.7426	571.6043	63.6725	0
	Automated time based control (scenario4)	0.0015	528.7474	584.0253	68.8348	0
	Integrated dynamic shading & lighting (scenario7)	0.0054	566.955	624.741	89.5409	0
Lighting energy (MWh)	Baseline model (scenario1)	489.9812	489.9812	489.9812	489.9812	489.9812
	Static manual control (scenario2)	489.9812	489.9812	489.9812	489.9812	489.9812
	Dynamic manual control (scenario3)	489.9812	489.9812	489.9812	489.9812	489.9812
	Automated time based control (scenario4)	489.9812	489.9812	489.9812	489.9812	489.9812
	Integrated dynamic shading & lighting (scenario7)	398.2326	407.8959	401.6172	403.1598	381.1681
Total energy (MWh)	Baseline model (scenario1)	3671.4692	3048.3362	3353.0081	2514.9431	3591.5464
	Static manual control (scenarioo2)	3628.4512	3043.9512	3356.6443	2479.9458	3498.2422
	Dynamic manual control (scenario3)	3630.0732	3047.9038	3392.064	2499.6106	3556.0867
	Automated time based control (scenario4)	3557.3433	3037.1707	3352.0117	2471.5381	3480.8845
	Integrated dynamic shading & lighting (scenario7)	3413.8862	2972.4817	3280.2173	2372.3323	3313.7583

Table 5-2 Summary of heating, cooling, lighting and total energy consumptions between various shading control strategies in kWh/m^2

Variables	Simulation scenarios	Abu Dhabi	Paris	Beijing	San Francisco	Singapore
Room cooling plant sensible load (kWh/m²)	Baseline model (scenario1)	151.567253	25.9173437	52.0698181	28.452394	143.029151
	Static manual control (scenario 2)	147.197831	22.0364054	47.0256397	22.5167938	133.551931
	Dynamic manual control (scenario3)	147.363813	24.1923113	49.995675	25.6488157	139.434221
	Automated time based control (scenario4)	139.974963	21.3582004	46.2217526	21.6606913	131.7888
	Integrated dynamic shading & lighting (scenario7)	134.865955	18.4781083	42.9429983	17.950358	126.009615
Room	Baseline model (scenario1)	0	30.4981151	32.7340928	3.03086311	0

heating plant sensible load (kWh/m²)	Static manual control (scenario2)	0	32.1644424	35.3597614	4.18564908	0
	Dynamic manual control (scenario3)	0.00010948	31.5508301	34.7659709	3.87267255	0
	Automated time based control (scenario4)	9.1233E-05	32.1593394	35.5214378	4.18665264	0
	Integrated dynamic shading & lighting (scenario7)	0.00032844	34.4831923	37.9978377	5.44603377	0
Lighting energy (kWh/m²)	Baseline model (scenario1)	29.8015115	29.8015115	29.8015115	29.8015115	29.8015115
	Static manual control (scenario2)	29.8015115	29.8015115	29.8015115	29.8015115	29.8015115
	Dynamic manual control (scenario3)	29.8015115	29.8015115	29.8015115	29.8015115	29.8015115
	Automated time based control (scenario4)	29.8015115	29.8015115	29.8015115	29.8015115	29.8015115
	Integrated dynamic shading & lighting (scenario7)	24.2212016	24.8089403	24.4270589	24.5208825	23.1833089
Total energy (kWh/m²)	Baseline model (scenario1)	223.305163	185.405127	203.935803	152.963228	218.444119
	Static manual control (scenarioo2)	220.688733	185.138423	204.156963	150.834631	212.769194
	Dynamic manual control (scenario3)	220.787386	185.378827	206.311251	152.030678	216.287398
	Automated time based control (scenario4)	216.363826	184.726021	203.8752	150.32326	211.713469
	Integrated dynamic shading & lighting (scenario7)	207.638515	180.791523	199.50854	144.28939	201.548562

Table 5-3 Percentage change in cooling, heating load and the total energy consumption

| Variables	Percentage change vs baseline	Abu Dhabi	Paris	BeiJing	San Francisco	Singapore
Room cooling plant sensible load	% change_ static manual control(scenario2)	-2.88	-14.97	-9.69	-20.86	-6.63
	% change_ dynamic manual control(scenario3)	-2.77	-6.66	-3.98	-9.85	-2.51
	& change_ automated time based control(scenario4)	-7.65	-17.59	-11.23	-23.87	-7.86
	% change_ Integrated dynamic shading & lighting(scenario7)	-11.02	-28.70	-17.53	-36.91	-11.90
Room heating plant sensible load	% change_ static manual control(scenario2)	N/A	5.46	8.02	38.10	0.00
	% change_ dynamic manual control(scenario3)	N/A	3.45	6.21	27.77	0.00
	& change_ automated time based control(scenario4)	N/A	5.45	8.52	38.13	0.00
	% change_ Integrated dynamic shading & lighting(scenario7)	N/A	13.07	16.08	79.69	0.00
Lighting energy	% change_ static manual control(scenario2)	0.00	0.00	0.00	0.00	0.00
	% change_ dynamic manual control(scenario3)	0.00	0.00	0.00	0.00	0.00
	& change_ automated time based control(scenario4)	0.00	0.00	0.00	0.00	0.00
	% change_ Integrated dynamic shading & lighting(scenario7)	-18.72	-16.75	-18.03	-17.72	-22.21
Total energy consumption	% change_ static manual control(scenario2)	-1.17	-0.14	0.11	-1.39	-2.60
	% change_ dynamic manual control(scenario3)	-1.13	-0.01	1.16	-0.61	-0.99
	& change_ automated time based control(scenario4)	-3.11	-0.37	-0.03	-1.73	-3.08
	% change_ Integrated dynamic shading & lighting(scenario7)	-7.02	-2.49	-2.17	-5.67	-7.73
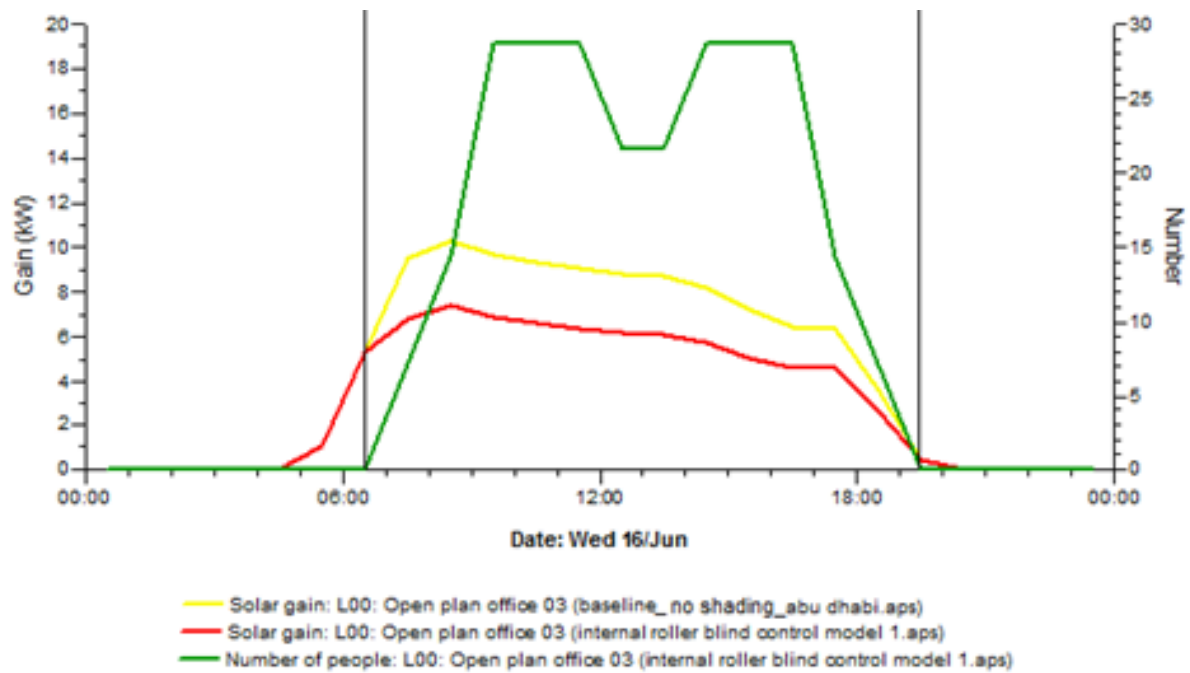
Figure 5-5 Comparison of solar gains with and without the static manual control with reference to the occupancy schedule
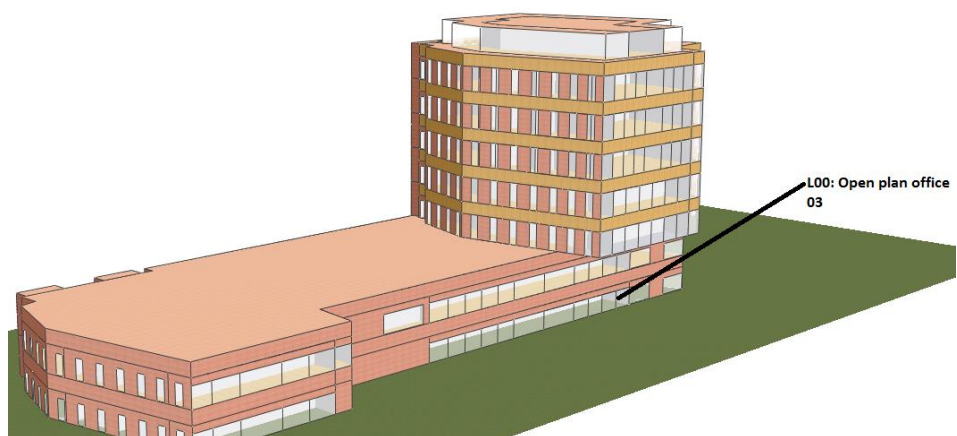
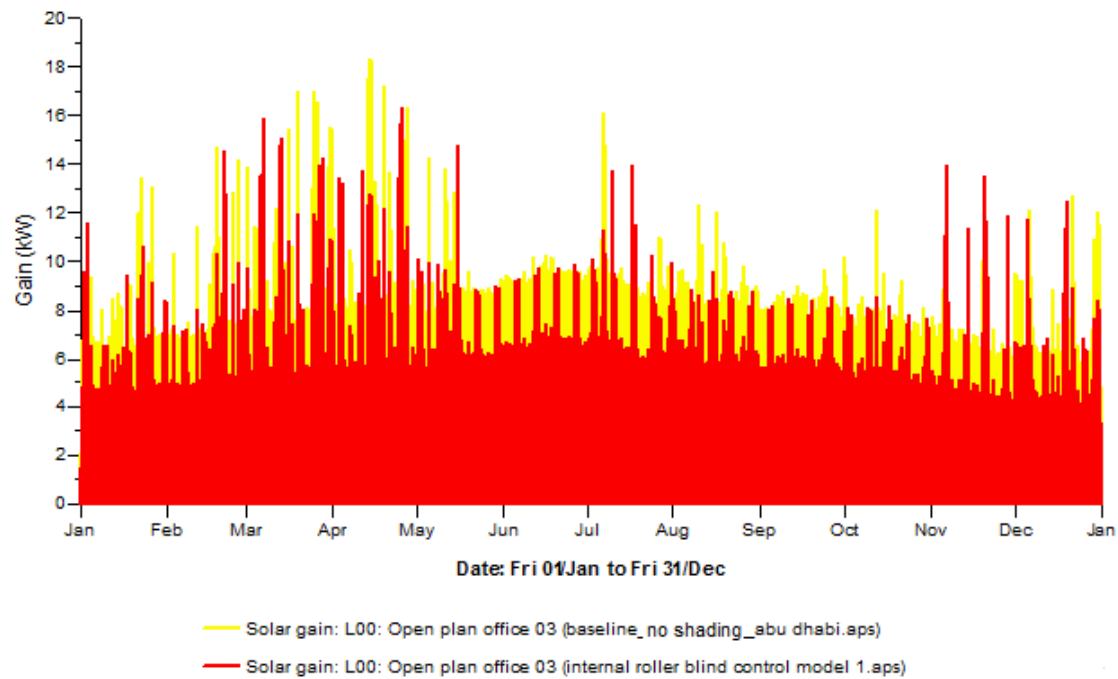

Figure 5-6 Location of the open plan office 03

Figure 5-7 Comparison of annual solar gains between with and without the static manual blind control

Figure 5-8 compares the overall system loads and energy performance of the static manual control model with the baseline model and Figure 5-9 further indicates the percentage changes in the room cooling sensible load, room heating sensible load and the total energy consumption between these two models. As shown in both graphs, due to the reduction in solar gains caused by the roller blinds, it has resulted in a decrease in the cooling load, an increase in the heating load and an overall decrease in the total energy consumption for most locations except for Beijing. It can be seen that Singapore achieved the most reduction in the total energy consumption by 2.6%, which was 93 MWh. This is due to its long period of hot weather across over the whole year. As mentioned previously, nearly 75% of the year (6514 hours) the dry-bulb air temperature remains between 25 $^{\circ}$C and 30 $^{\circ}$C. Although Abu Dhabi has the hottest summer over the five locations, it has not achieved a similar amount of energy savings as Singapore has. This is due to its rather cool weather conditions from November to March in which the dry-bulb air temperature is seen to drop between 12 $^{\circ}$C to 25 $^{\circ}$C, therefore it is not surprised to see that the reduction in the total energy consumption for Abu Dhabi was 43 MWh. San Francisco has a cool to mild weather condition for the most of the year; hence it has achieved a notable reduction by 1.4% in the total energy consumption.

It is noted that the total energy consumption for Paris was only slightly reduced but for Beijing it was slightly increased instead. This is due to the fact that the energy saving from the cooling demand is less than the increased heating energy consumption. Amongst the five locations, Beijing has the coldest winter period with the lowest dry-bulb temperature down to -14°C while the rest of locations have the lowest air temperatures mainly above 0°C except for Paris which is down to -8°C. In addition, Beijing has a quite long winter period normally from early November to the March. Table 5-4 shows the hours that the ambient dry-bulb temperatures are below -10°C, -5°C , 0°C and 5 $^{\circ}$C respectively for the five locations over the whole year. Therefore, it is important to be able to maximise the benefit from the solar gains in winter for climatic locations such as Beijing. It can also be concluded that this type of simple blind control is not the appropriate approach for Beijing location.

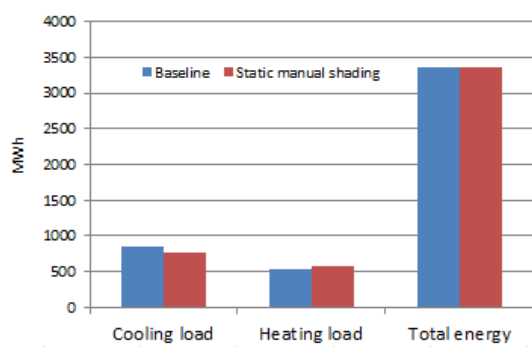Table 5-4 Hours in range for various ambient dry-bulb temperatures

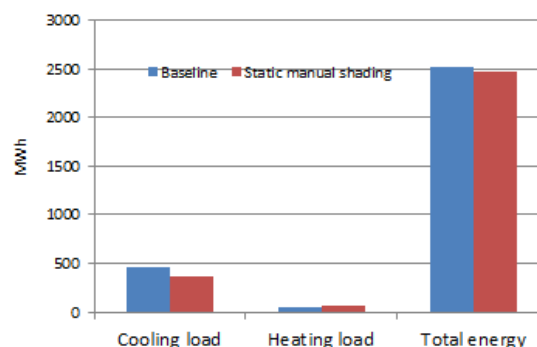| Locations	Dry-bulb temperature –hours in range			
	< 5 °C	< 0 °C	< -5 °C	< -10 °C
Paris	1883	454	44	0
SanFrancisco	209	2	0	0
Singapore	0	0	0	0
Beijing	2739	1490	430	27
Abu Dhabi	1	0	0	0
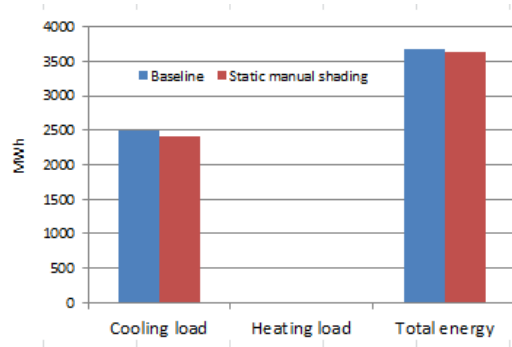
(a) Abu Dhabi
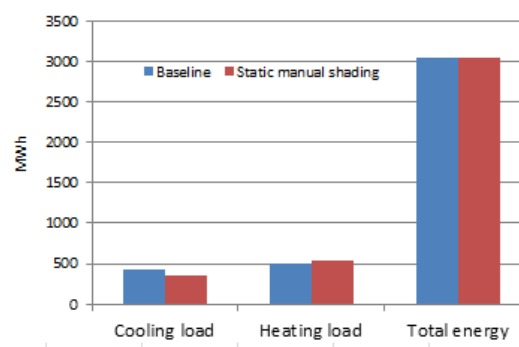
(b) Paris

(c) Beijing

(d) San Francisco
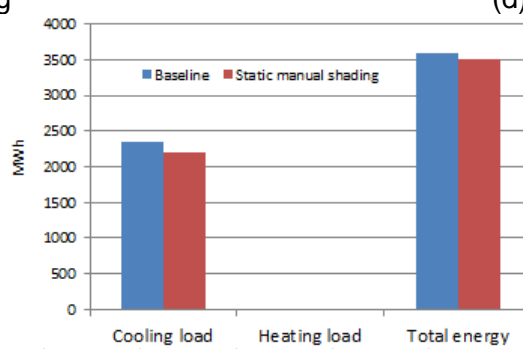
(e) Singapore
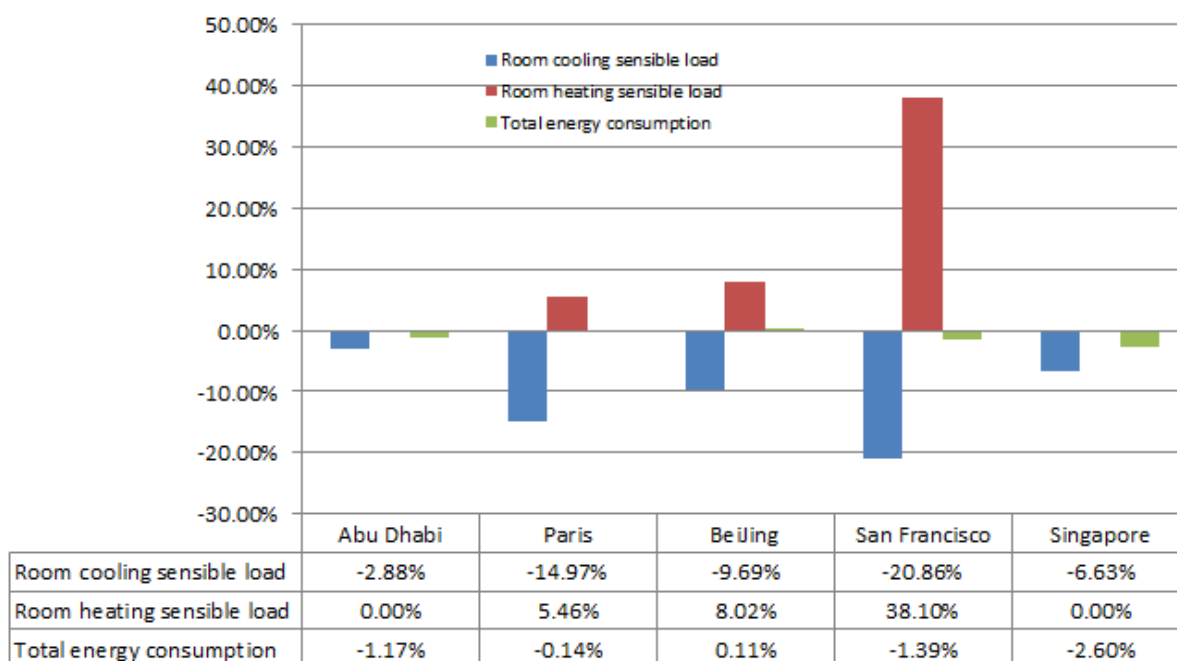
Figure 5-8 Comparison of the static manual blind control with baseline model (no blind)

	Abu Dhabi	Paris	Beijing	San Francisco	Singapore
Room cooling sensible load	-2.88%	-14.97%	-9.69%	-20.86%	-6.63%
Room heating sensible load	0.00%	5.46%	8.02%	38.10%	0.00%
Total energy consumption	-1.17%	-0.14%	0.11%	-1.39%	-2.60%

Figure 5-9 Percentage changes between static manual blind control model and the baseline model

5.1.3 Dynamic manual blind control (scenario 3)

In comparison with the static manual control strategy, the dynamic manual blind control is mainly based on the internal illuminance level rather than the occupancy schedule. Once the blind is closed, it remains in the lowered position until the next day upon the first arrival. The control logic can be illustrated by comparing the space cooling sensible load and space air temperature between the baseline model and the dynamic manual control model with reference to the level of the internal illuminance and solar radiations based on open plan office 06 (located on the ground floor and west side of the building), as shown in Figure 5-10. It can be seen that due to the different air temperatures in the very early morning between the two models, the required cooling loads were different in the first 2h pre-cooling period. The cooling loads then became similar after 07:00 am. However, the cooling load of the dynamic manual control model started gradually reducing when the internal illuminance reached the manual control threshold of 5000lux. After 19:00 the plant system was turned off, therefore the cooling load was down to zero. However, the blind remained closed until the next morning at 07:00am. As shown in the figure, there was still a certain amount of solar radiations available after 19:00. The blind position therefore was able to further reduce the solar gains in the room, which led to a slightly lower room air temperature during the whole night compared to the temperatures without any shading device in the baseline model.
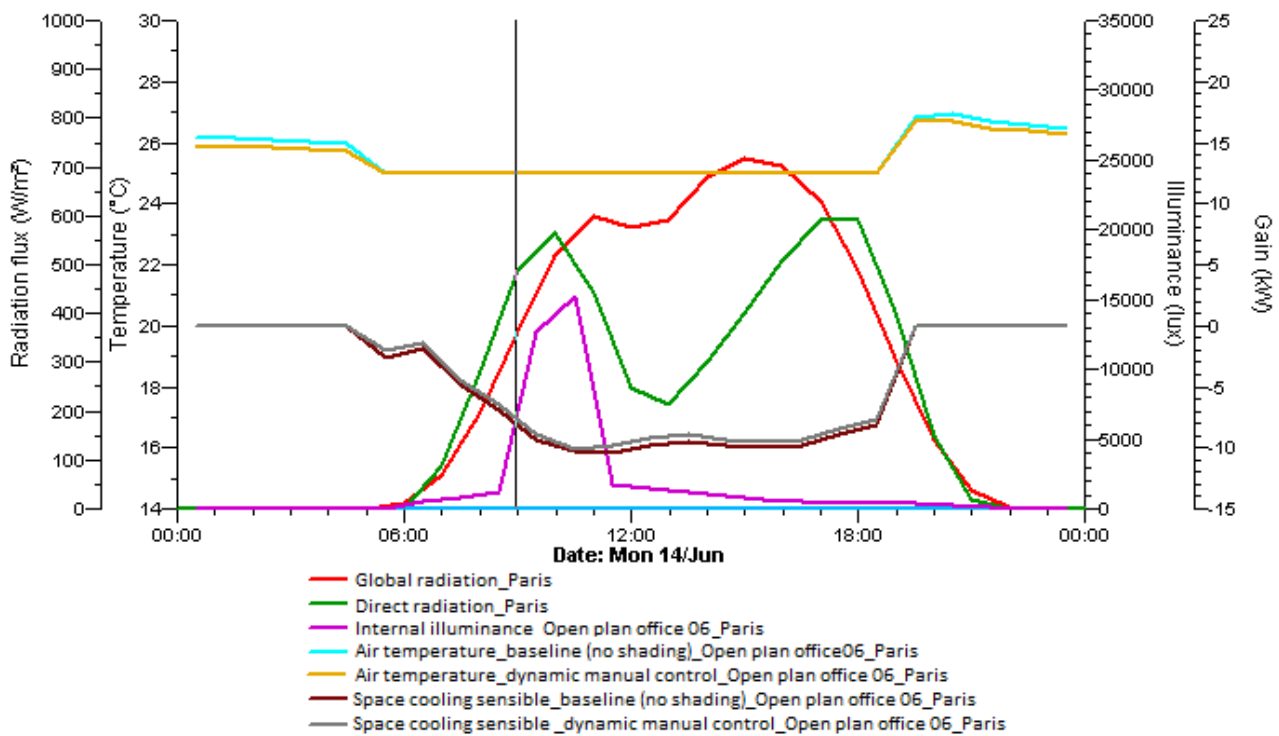
Figure 5-10 Comparison of space cooling sensible load and air temperature between dynamic manual control model and baseline model based on open plan office 06

Figure 5-11 shows results of annual cooling and heating loads as well as the total energy consumption of the baseline model, static manual control model and dynamic manual control model. Figure 5-12 displays the percentage changes in the cooling load, heating load and the total energy consumption when comparing the dynamic manual control with the baseline (no blind control) and the static manual control respectively. Both figures have clearly indicated that since employing the dynamic manual blind control, the cooling load has reduced compared to the baseline; however the reduction was less than that achieved by the static manual control due to the amount of blocked solar gains. Similarly, the heating load has been increased; however the increase was less than that caused by the static manual control except for Abu Dhabi. This results from less number of hours that the blind was in closed position during the occupied period for the dynamic manual control. Table 5-5 sets up an example based on open plan office 04 for both cooling and heating modes to demonstrate how the blind was positioned in both static and dynamic manual control strategies. It can be seen that in the cooling mode the blind was closed for 13 hours from 07:00 to 19:00 during the occupied period in the static manual control scenario for BeiJing location. For the dynamic manual control the bind was manually closed at 11:00am when the internal illuminance was above 5000lux and remained this position till the next day, therefore the total closing hours were 13 hours during the occupied period; however there were only 9 hours in the occupied period which led to a lower cooling load compared to the static manual control. Likewise, in the heating mode the blind was closed for 13 hours during the occupied period for the static manual control and in total 15 hours for the dynamic manual blind control but only 4 hours during the occupied period which allows a certain amount of solar gains incoming to the space and thereafter led to a less increase in the heating load. It is worth mentioning that the heating was supplied on continuously with two different set points and the total hours of the blind being closed were overall longer in the dynamic manual blind control scenario. Moreover, Abu Dhabi has the highest global solar radiation amongst the five climatic locations and tends to have solar radiations out of the occupied period. Consequently there were more solar gains being blocked by the dynamic manual blind control than that by the static manual blind control for Adu Dhabi, which therefore led to a higher heating sensible load for the dynamic manual control.

Overall, the total energy consumption was reduced for Abu Dhabi, Singapore and San Francisco but slightly increased for Beijing when comparing to the baseline model. As mentioned previously,
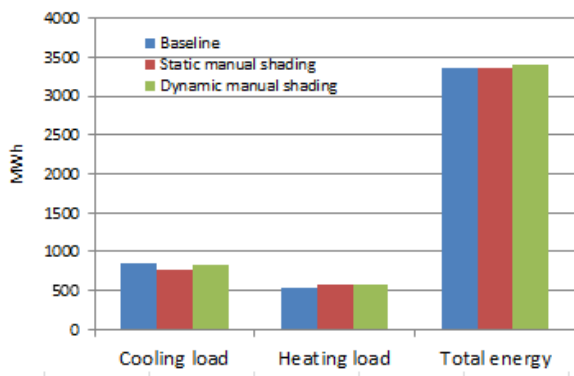
this is due to the trade-off between the reduced cooling load and the increased heating load.
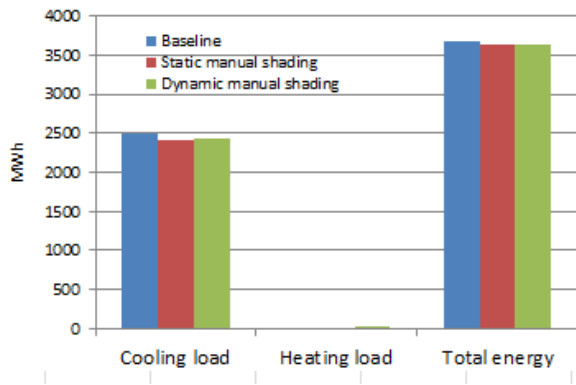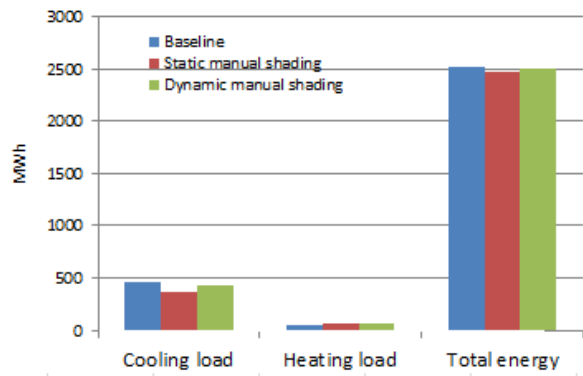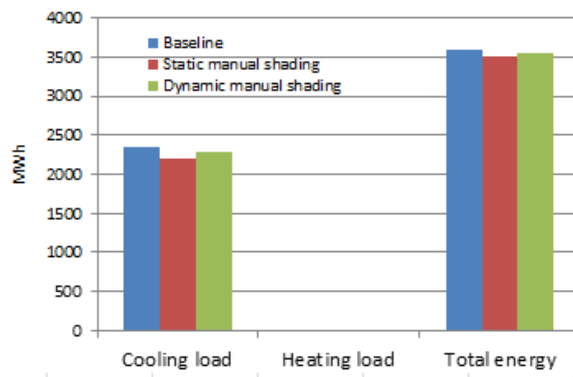

(a) Abu Dhabi
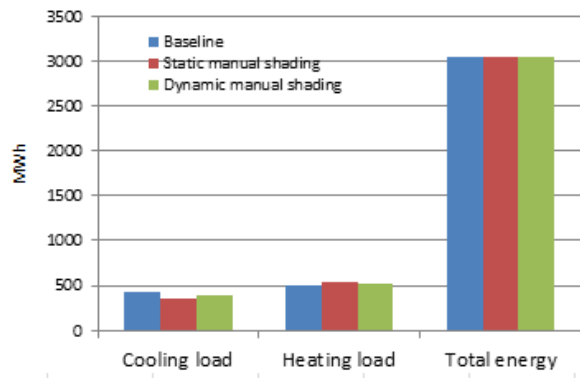
(b) Paris

(c) Beijing

(d) San Francisco

(e) Singapore

Figure 5-11 Comparison of the dynamic manual blind control with both no blind control (baseline) and static manual control
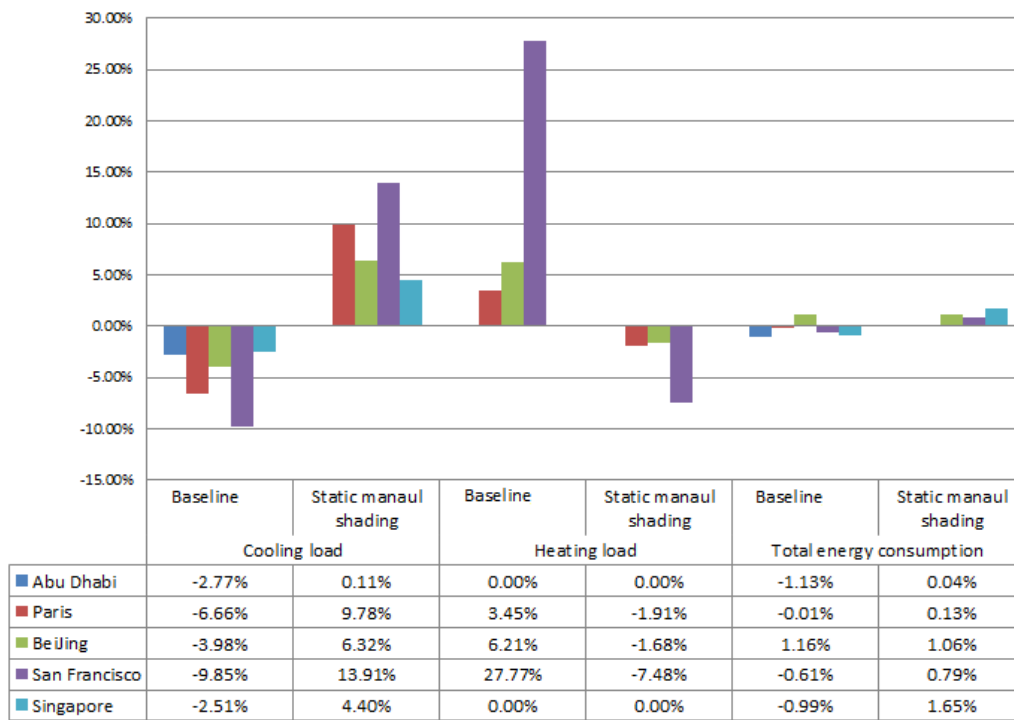
	Baseline	Static manaul shading	Baseline	Static manaul shading	Baseline	Static manaul shading
	Cooling load		Heating load		Total energy consumption	
Abu Dhabi	-2.77%	0.11%	0.00%	0.00%	-1.13%	0.04%
Paris	-6.66%	9.78%	3.45%	-1.91%	-0.01%	0.13%
Beijing	-3.98%	6.32%	6.21%	-1.68%	1.16%	1.06%
San Francisco	-9.85%	13.91%	27.77%	-7.48%	-0.61%	0.79%
Singapore	-2.51%	4.40%	0.00%	0.00%	-0.99%	1.65%

Figure 5-12 Percentage changes between dynamic manual control and baseline model and between dynamic manual control and static manual control

Table 5-5 Comparison of blind positions for both cooling and heating modes based on open plan office 04 for Beijing location

Time	Cooling mode (24th May)			Heating mode (29th Jan.)		
	Blind position		Internal illuminance (lux)	Blind position		Internal illuminance (lux)
	Static manual control.	Dynamic manual control		Static manual control.	Dynamic manual control	
00:00	0	0	0	0	1	0
01:00	0	0	0	0	1	0
02:00	0	0	0	0	1	0
03:00	0	0	0	0	1	0
04:00	0	0	155	0	1	0
05:00	0	0	1366	0	1	0
06:00	0	0	3205	0	1	0
07:00	1	0	2539	1	0	107
08:00	1	0	2896	1	0	255
09:00	1	0	3739	1	0	374
10:00	1	0	4788	1	0	362
11:00	1	1	5256	1	0	236
12:00	1	1	5308	1	0	183
13:00	1	1	5028	1	0	234
14:00	1	1	4146	1	0	366
15:00	1	1	2830	1	0	518
16:00	1	1	1626	1	1	5761
17:00	1	1	829	1	1	720

18:00	1	1	320	1	1	0
19:00	1	1	64	1	1	0
20:00	0	1	0	0	1	0
21:00	0	1	0	0	1	0
22:00	0	1	0	0	1	0
23:00	0	1	0	0	1	0

### 5.1.4 Automated time based blind control (scenario 4)

The automated time based blind control was designed mainly based on the availability of the external illuminance, occupancy period and space conditioning mode. Figure 5-13 illustrates the calculated annual hourly external illuminance values of the office building model for the five selected climatic locations. It can be seen that for Abu Dhabi, Singapore and San Francisco, the external illuminance levels were well above the blind control threshold which is 15000 lux whilst for Paris the external illuminance values fell below the threshold mainly in the winter season and for Beijing it exceeded the control threshold for the most of the time. Hence, it demonstrates that the setting of the blind control threshold was reasonable for the studied locations. In addition, the variation pattern of the calculated external illuminance for each location correctly reflected the associated local global solar radiations.
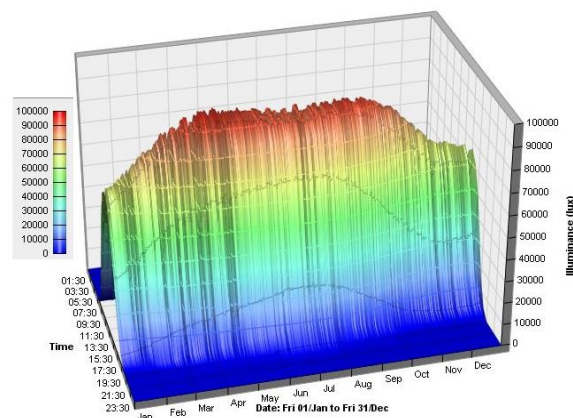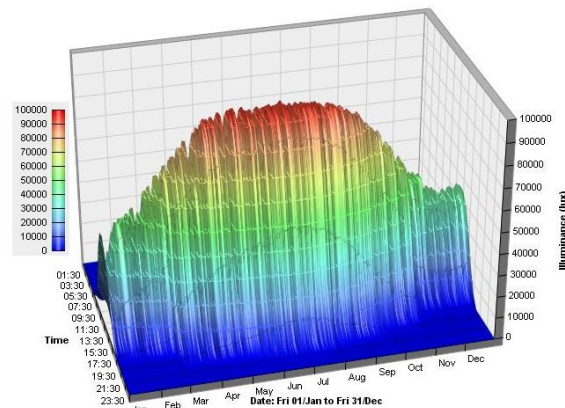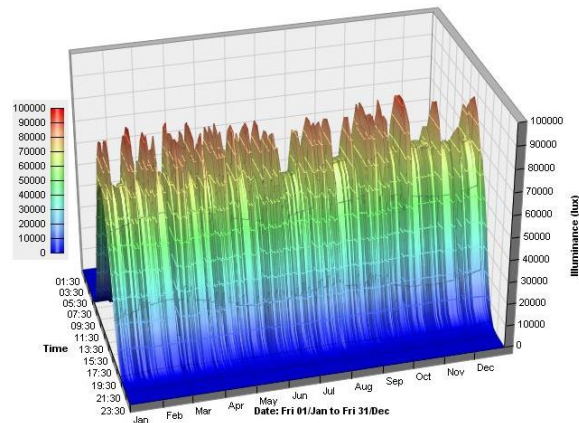

(a) Abu Dhabi
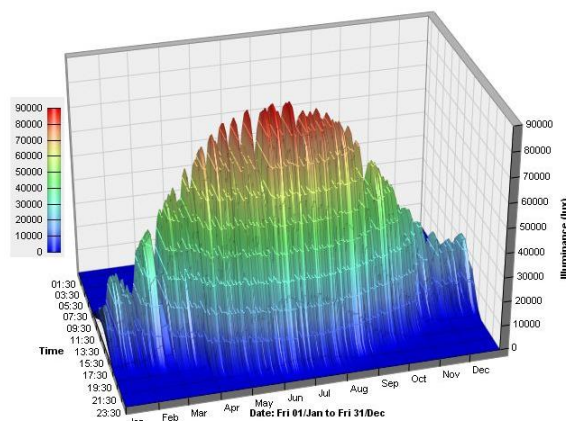
(b) Paris
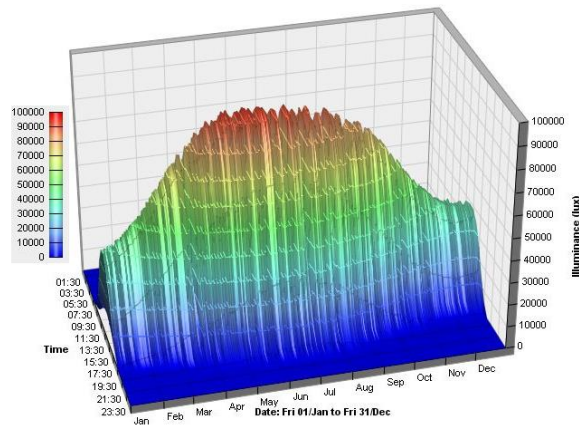
(c) Beijing

(d) San Francisco

(e) Singapore

Figure 5-13 External illuminance for the five climatic locations

Figure 5-14 compares the cooling load, heating load and the total energy consumption between all the investigated shading control strategies for the five climatic locations. Figure 5-15 shows the corresponding percentage changes between the time based switching blind control and the baseline scenario (no shading). As indicated in the two figures, it can be seen that for all the locations the cooling loads were reduced in a range from 7.7% to 24% compared to the baseline model. Given the absolute values, Abu Dhabi and Singapore achieved the most cooling load reductions which are 191 MWh and 185 MWh in turn whilst Paris and Beijing had the least cooling load reductions of 75 MWh and 96 MWh respectively. Due to abundant solar radiations, San Francisco managed a reduction of 112 MWh. Meanwhile the heating loads of the office building model were slightly increased by 0.0015 MWh, 27.3 MWh, 45.8 MWh and 19.0 MWh individually

for Abu Dhabi, Paris, Beijing and San Francisco, which resulted from the reduced solar gains by lowering the blinds. As pointed out earlier, Beijing has the coldest and longest winter period compared with other locations and Abu Dhabi has the hottest summer period but a wide seasonal temperature variation, therefore they received the most and the least heating load increase respectively.
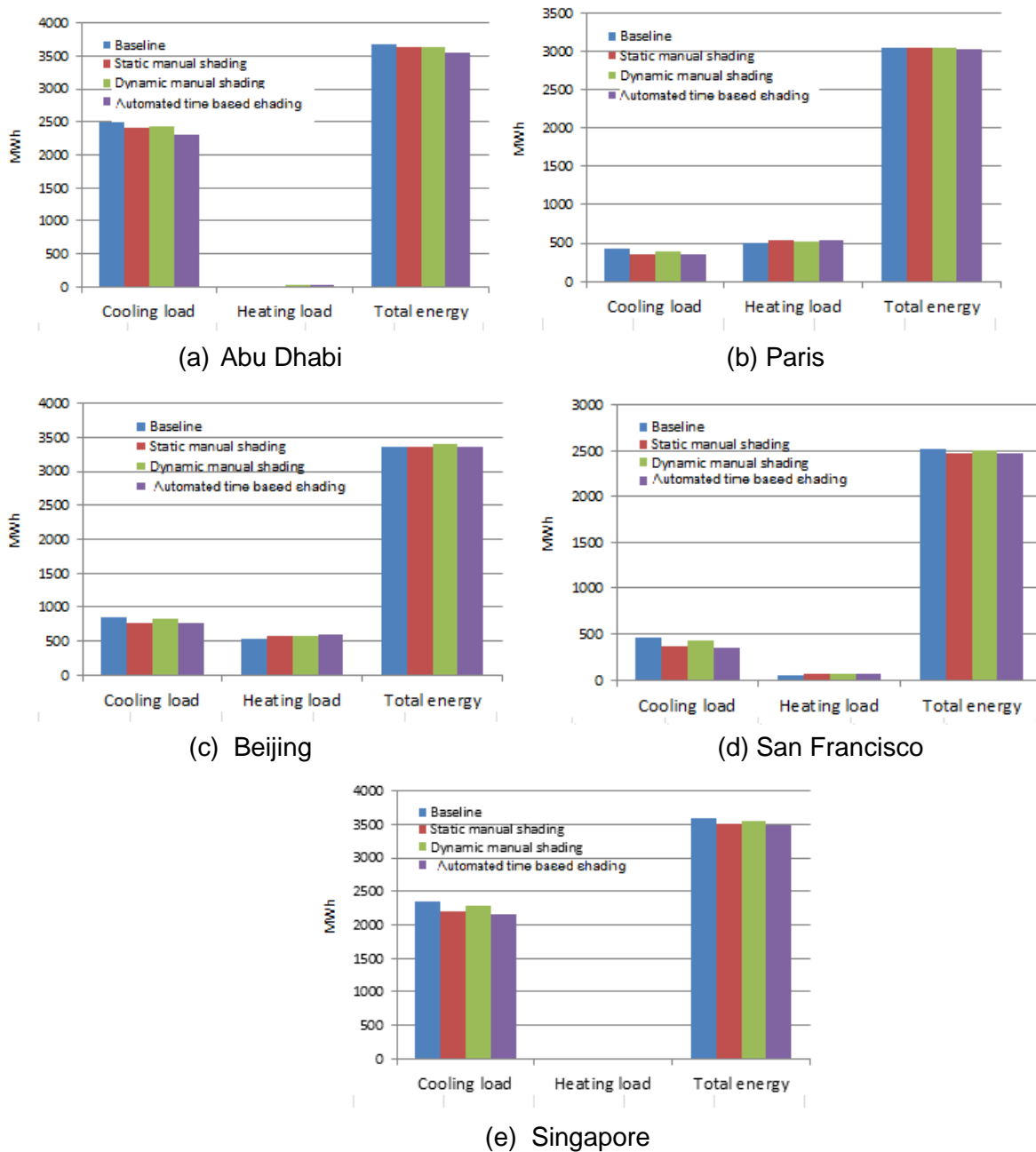

(a) Abu Dhabi

(b) Paris

(c) Beijing

(d) San Francisco

(e) Singapore

Figure 5-14 Comparison of cooling load, heating load and the total energy consumption between all the blind control strategies

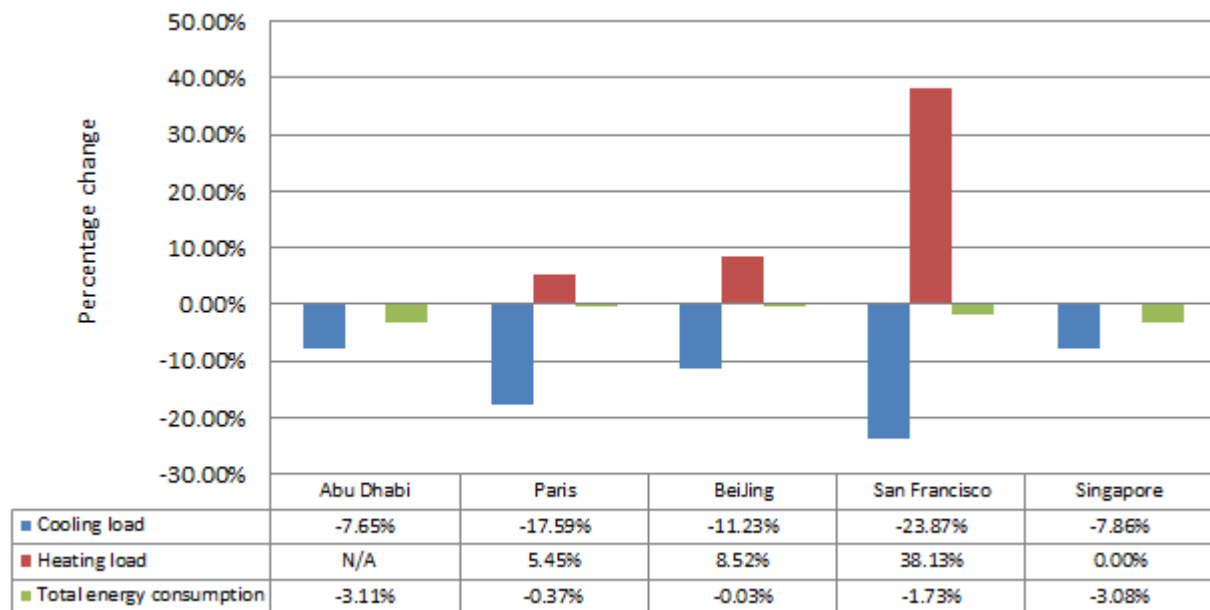|	Abu Dhabi	Paris	BeiJing	San Francisco	Singapore
■ Cooling load	-7.65%	-17.59%	-11.23%	-23.87%	-7.86%
■ Heating load	N/A	5.45%	8.52%	38.13%	0.00%
■ Total energy consumption	-3.11%	-0.37%	-0.03%	-1.73%	-3.08%

Figure 5-15 Percentage changes between baseline and automated time based control models

Overall, the total energy consumption for all the five climatic locations was reduced when comparing to the baseline model. As expected, Abu Dhabi and Singapore succeeded the most energy reductions by 114 MWh and 111 MWh respectively whilst Beijing only received a slight energy reduction of 1 MWh. This implies that the impact of the shading control on the energy consumption is climate dependent. It has more influence on warmer climates with less heating demand. It is also noted that amongst all the investigated shading control strategies, the automated time basedcontrol was the only attempt which successfully achieved energy savings across all the selected climatic locations. It demonstrates that this type of automated blind control does consider different control strategies in terms of exploiting usage of solar gains in different seasons, which is minimising the solar gains in the cooling mode and maximising the solar gains in the heating mode. In addition, in order to maximise the benefit from employing the automated blind control for a climate with a hot summer and a cold winter such as Beijing, it suggests designing a further fine-tuned control strategy to tailor the local weather conditions, such as changes in the threshold of the external illuminance level or the definition of the heating and cooling modes (set point).

5.1.5 Integrated dynamic shading & lighting control (scenario7)

Figures 5-16 to 5-19 compare the cooling load, heating load and the total energy consumption respectively between all the investigated shading control strategies as well as the integrated dynamic shading and lighting control strategy. As shown in these graphs, the integrated dynamic shading & lighting control strategy was able to reduce more cooling load and the total energy consumption compared with all the other shading control strategies. This is simply due to the additional deployment of the occupancy based switching & daylight dimming control, which led to a reduction in the annual lighting energy consumption up to nearly 109 MWh, as shown in Figure 5-18. The reduced lighting energy prompted an increase in the heating load, however due to the trade-off between the heating, cooling and lighting energy uses; the total energy consumption was actually reduced over the five climatic locations from 73 MWh to 278 Mwh. So far, the study has demonstrated that the integrated approach offers an energy efficient solution.
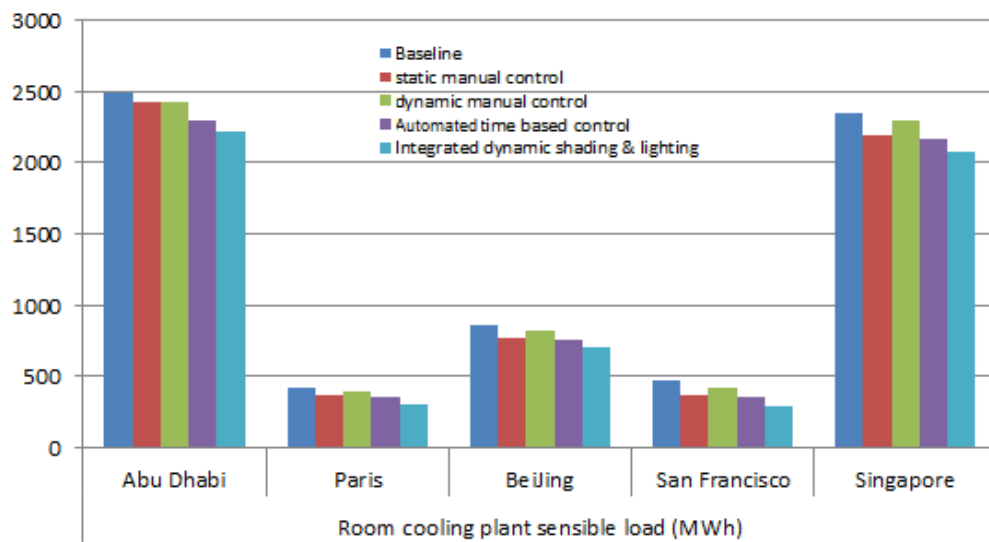
Figure 5-16 Comparison of cooling load between all the shading control scenarios
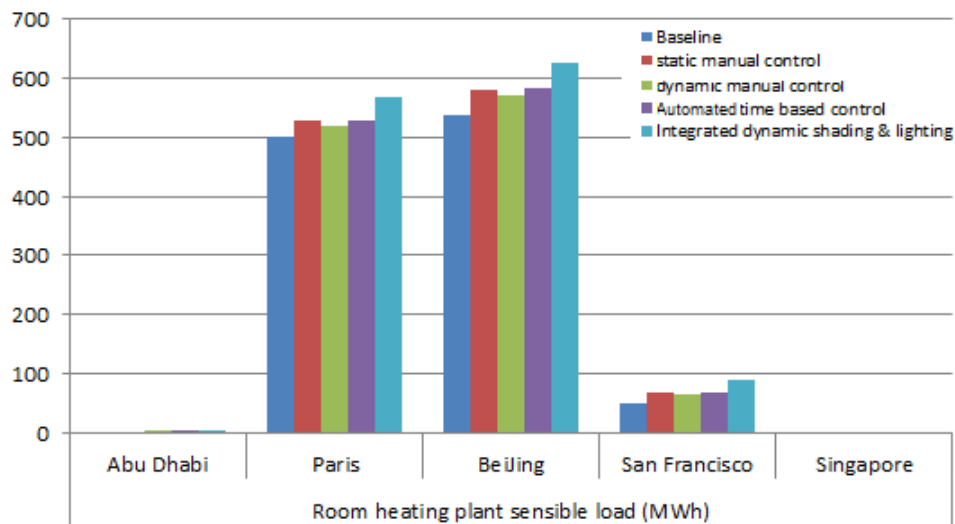

Figure 5-17 Comparison of heating load between all the shading control scenarios
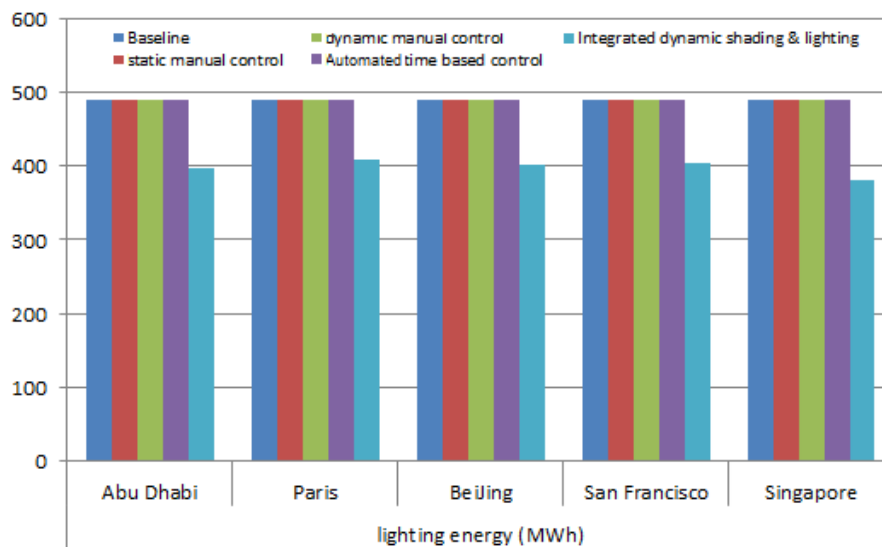

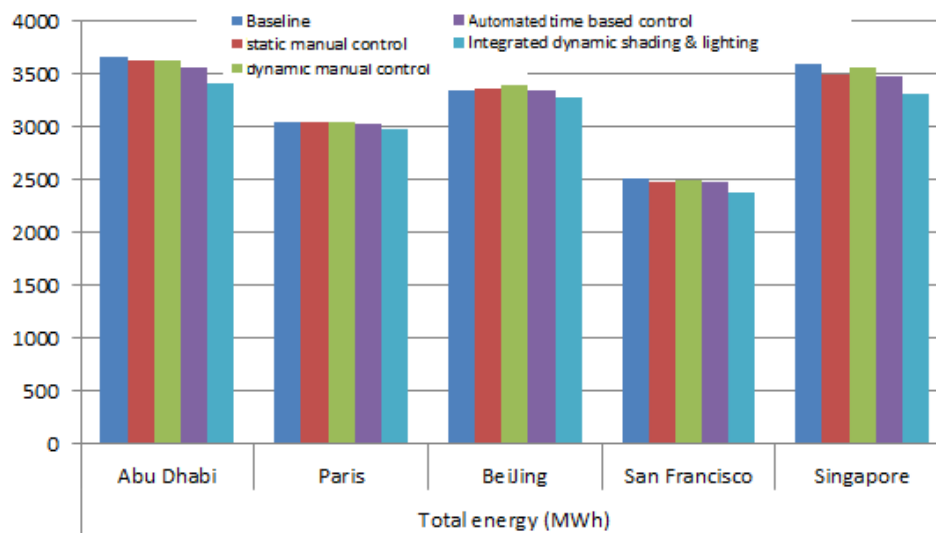Figure 5-18 Comparison of lighting between all the shading control scenarios

Figure 5-19 Comparison of the total energy consumption between all the shading control scenarios

5.1 Lighting control analysis

5.2.1 Occupancy based switching lighting control (scenario 5)

Figures 5-20 to 5-23 compare the cooling load, heating load, lighting energy and the total energy consumption respectively between all the investigated lighting control strategies which are the manual lighting control (baseline model), occupancy based switching control and occupancy based switching & daylight dimming control for the five climatic locations. Table 5-6 and Table 5-7 summary values of the cooling load, heating load, lighting energy and the total energy consumption of these investigated lighting controls with different units and Table 5-8 presents the corresponding percentage changes for the two types of occupancy based switching controls against the manual lighting control.
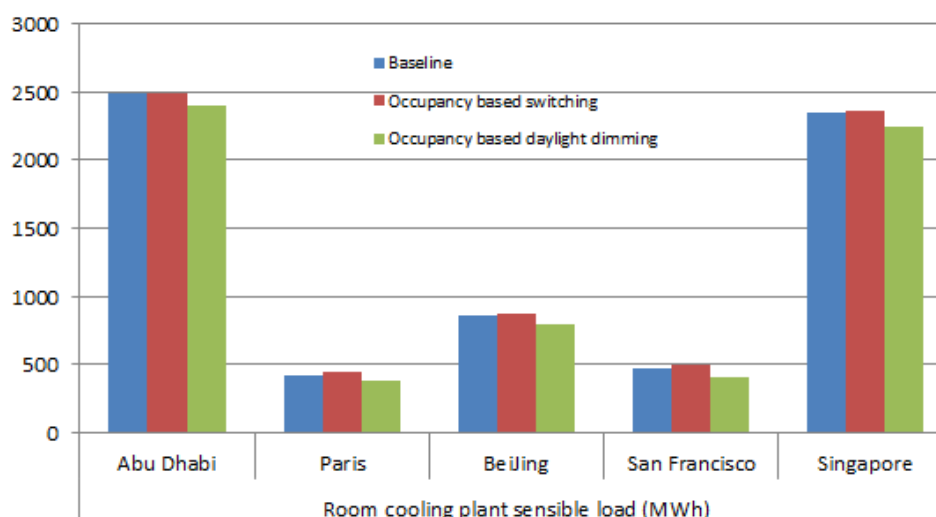

Figure 5-20 Comparison of the cooling load between all the lighting control scenarios
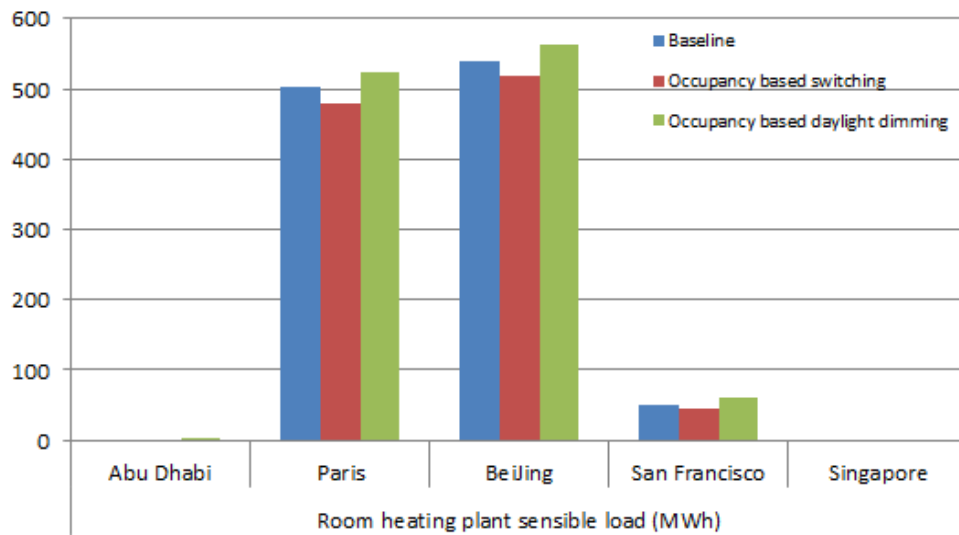
Figure 5-21 Comparison of the heating load between all the lighting control scenarios
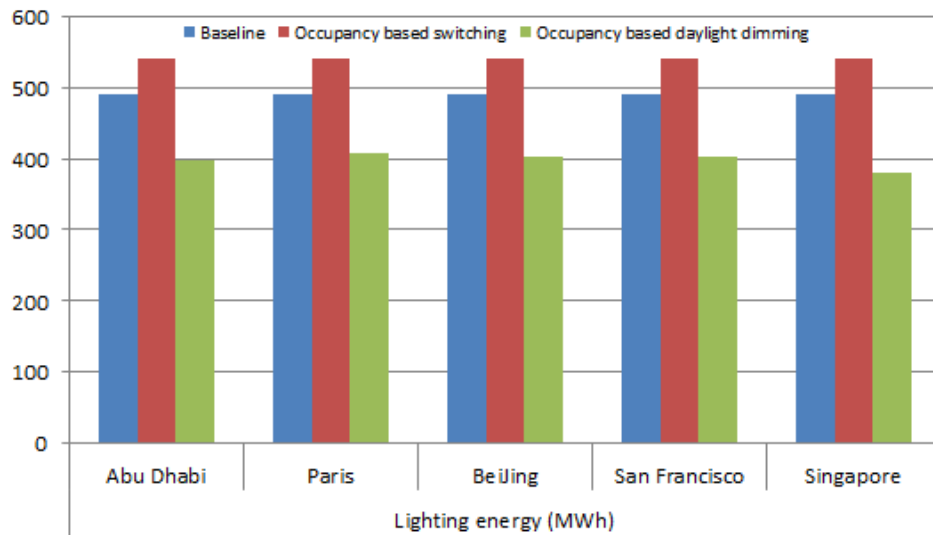

Figure 5-22 Comparison of the lighting energy between all the lighting control scenarios
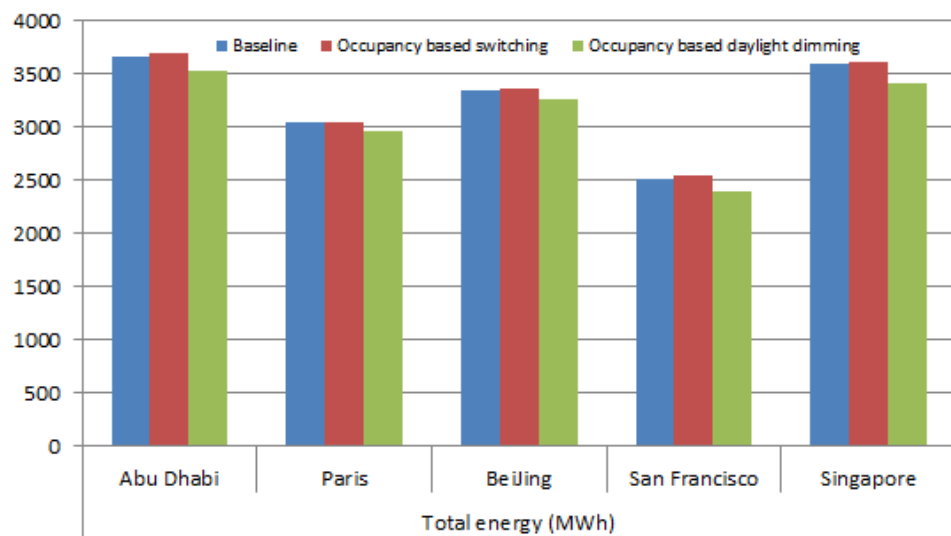

Figure 5-23 Comparison of the total energy consumption between all the lighting control scenarios

Table 5-6 Summary of heating, cooling, lighting and total energy consumptions between various lighting control strategies

Variables	Simulation scenarios	Abu Dhabi	Paris	Beijing	San Francisco	Singapore
Cooling load (MWh)	Manual lighting control (scenario1	2491.99	426.12	856.12	467.80	2351.61
	Occupancy based switching (scenario5)	2487.64	439.90	867.04	491.98	2355.07
	Occupancy based switching & daylight dimming (scenario 6)	2403.37	378.52	801.47	406.83	2247.15
Heating load (MWh)	Manual lighting control (scenario1	0.00	501.43	538.20	49.83	0.00
	Occupancy based switching (scenario5)	0.00	478.27	518.25	44.25	0.00
	Occupancy based switching & daylight dimming (scenario 6)	0.00	523.19	562.94	59.55	0.00
Lighting energy (MWh)	Manual lighting control (scenario1	489.98	489.98	489.98	489.98	489.98
	Occupancy based switching (scenario5)	540.89	540.89	540.89	540.89	540.89
	Occupancy based switching & daylight dimming (scenario 6)	398.23	407.90	401.62	403.16	381.17
Total energy (MWh)	Manual lighting control (scenario1	3671.47	3048.34	3353.01	2514.94	3591.55
	Occupancy based switching (scenario5)	3693.78	3052.90	3359.84	2547.45	3618.54
	Occupancy based switching & daylight dimming (scenario 6)	3525.24	2963.19	3261.06	2402.20	3418.77

Table 5-7 Summary of heating, cooling, lighting and total energy consumption between various lighting control strategies in kWh/m²

Variables	Simulation scenarios	Abu Dhabi	Paris	Beijing	San Francisco	Singapore
Cooling load (kWh/m²)	Manual lighting control (scenario1	151.57	25.92	52.07	28.45	143.03
	Occupancy based switching (scenario5)	151.30	26.76	52.73	29.92	143.24
	Occupancy based switching & daylight dimming (scenario 6)	146.18	23.02	48.75	24.74	136.68
Heating load (kWh/m²)	Manual lighting control (scenario1)	0.00	30.50	32.73	3.03	0.00
	Occupancy based switching (scenario5)	0.00	29.09	31.52	2.69	0.00
	Occupancy based switching & daylight dimming (scenario 6)	0.00	31.82	34.24	3.62	0.00
Lighting energy (kWh/m²)	Manual lighting control (scenario1	29.80	29.80	29.80	29.80	29.80
	Occupancy based switching (scenario5)	32.90	32.90	32.90	32.90	32.90
	Occupancy based switching & daylight dimming (scenario 6)	24.22	24.81	24.43	24.52	23.18
Total energy (kWh/m²)	Manual lighting control (scenario1	223.31	185.41	203.94	152.96	218.44
	Occupancy based switching (scenario5)	224.66	185.68	204.35	154.94	220.09
	Occupancy based switching & daylight dimming (scenario 6)	214.41	180.23	198.34	146.11	207.94

Table 5-8 Percentage change in cooling, heating load, lighting energy and the total energy consumption

Variables	Percentage change vs baseline	Abu Dhabi	Paris	BeiJing	San Francisco	Singapore
Cooling load	% change_ Occupancy based switching	-0.17	3.23	1.28	5.17	0.15
	% change_ Occupancy based switching & daylight dimming	-3.56	-11.17	-6.38	-13.03	-4.44
Heating load	% change_ Occupancy based switching	0.00	-4.62	-3.71	-11.20	0.00
	% change_ Occupancy based switching & daylight dimming	0.00	4.34	4.60	19.51	0.00
Lighting energy	% change_ Occupancy based switching	10.39	10.39	10.39	10.39	10.39
	% change_ Occupancy based switching & daylight dimming	-18.72	-16.75	-18.03	-17.72	-22.21
Total energy consumption	% change_ Occupancy based switching	0.61	0.15	0.20	1.29	0.75
	% change_ Occupancy based switching & daylight dimming	-3.98	-2.79	-2.74	-4.48	-4.81

Figure 5-24 illustrates percentage changes in cooling load, heating load, lighting energy and the total energy consumption respectively over the five locations when comparing the occupancy based switching model against the baseline model. It is interesting to see that the cooling load, lighting energy and the total energy consumption have been increased whilst the heating load has been decreased, which does not fit into the normal expectation. This is solely due to the settings of the manual lighting control and the occupancy based switching control adopted by this study. As explained previously, an optimistic assumption of the manual lighting control has been employed to illustrate a scenario which is not extremely energy intensive. The manual lighting control indicates that all lights are on at 90% during the occupied period and at 5% during the un-occupied period for weekdays and lights are all off during weekends. For the occupancy based switching control, during the weekdays lights are automatically full on when occupants are present for perimeter zones with a 15min time-out and off otherwise. For core zones the lights are turned full on during the occupied period and turned to 10% during the un-occupied period. During the weekends lights are also off. Furthermore, the core zones account for 49% of the building model which is a quite considerably large area. Hence, the occupancy based switching control model actually has consumed a higher lighting gains than that of the manual lighting control model, which leads to a higher cooling load and a lower heating load. Based on the trade-off between the cooling, heating and lighting energy consumptions, the total energy consumption was therefore increased between 0.15% and 1.29% for the five locations.
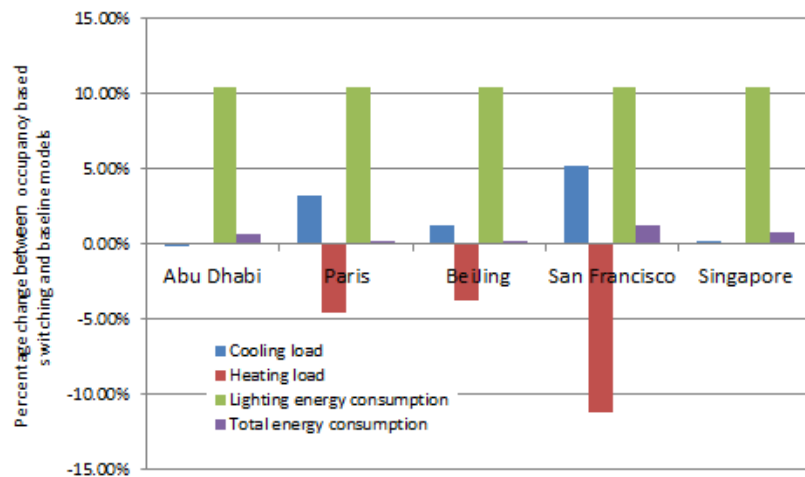
Figure 5-24Percentage changes between occupancy based switching model and baseline model

5.2.2   Occupancy based switching & daylight dimming control (scenario6)

Percentage changes in the cooling load, heating load, lighting energy and the total energy consumption in comparison of the occupancy based switching control against the baseline manual lighting control are shown in Figure 5-25. It can be seen that the total energy consumption has been decreased from 2.7% up to 4.8% and the cooling load has also been reduced between 3.6% and 13.0% over the five climatic locations. This is due to the reductions in the lighting energy consumption since introducing the daylight dimming strategy. This can also be clearly demonstrated in Figure 5-26, which compares the occupancy based switching & daylight dimming control with the occupancy based switching control in terms of changes in system loads and energy consumptions. As indicated in both figures, the reduction in lighting gains leads to a decrease in the cooling load and an increase in the heating load. Due to the hot climatic conditions in both Abu Dhabi and Singapore, there is no heating requirement during the whole year; therefore the percentage change in the heating load is zero.
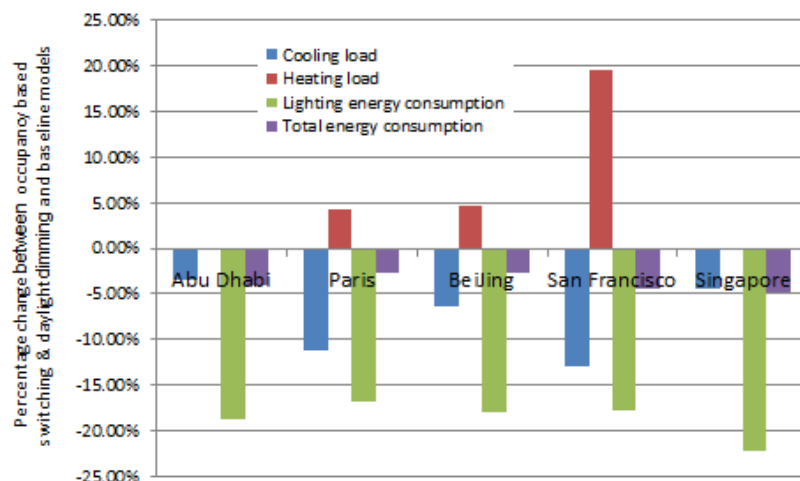

Figure 5-25 Percentage changes between occupancy based switching & daylight dimming model and the baseline model
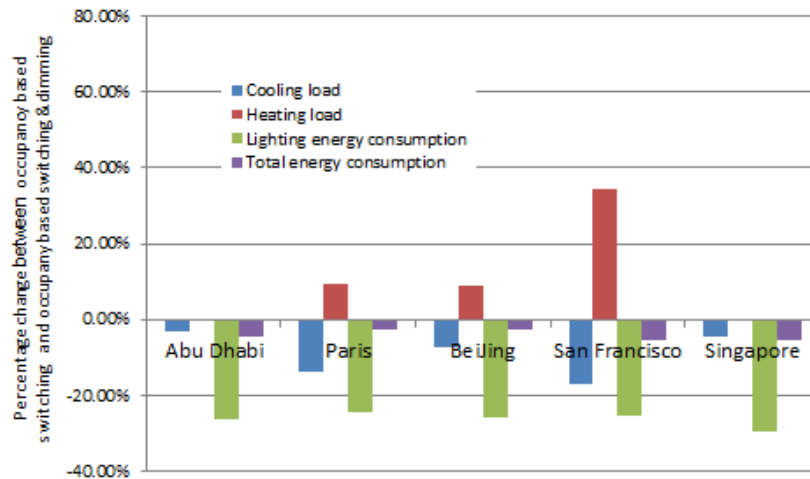
Figure 5-26 Percentage changes between occupancy based switching & daylight dimming model and the occupancy based switching model

To take a closer look at the dimming control, the lights are linearly dimmable from 0% to 100% based on the 650 lux set point of the internal illuminance. Figure 5-27 shows the availability of the internal illuminance and lighting gains of the open plan office 03 in a summer day when the dimming is on and off respectively for Abu Dhabi. As shown, the red colour line is the internal illuminance value of open plan office 03 and the horizontal black dot line is the dimming threshold line at 650 lux level. It can be seen that during the period where the internal illuminance value was dropped below the dimming threshold line as marked in the light blue block, the lighting gain in the navy blue colour started rising up from 0 kW. The yellow colour line is the lighting gain for the occupancy based switching control without dimming control. The difference between the yellow line and the red line is the impact of introducing the dimming control on the lighting gains. This has resulted in 87.37% reduction in the annual lighting gains, as shown in Figure 5-28.
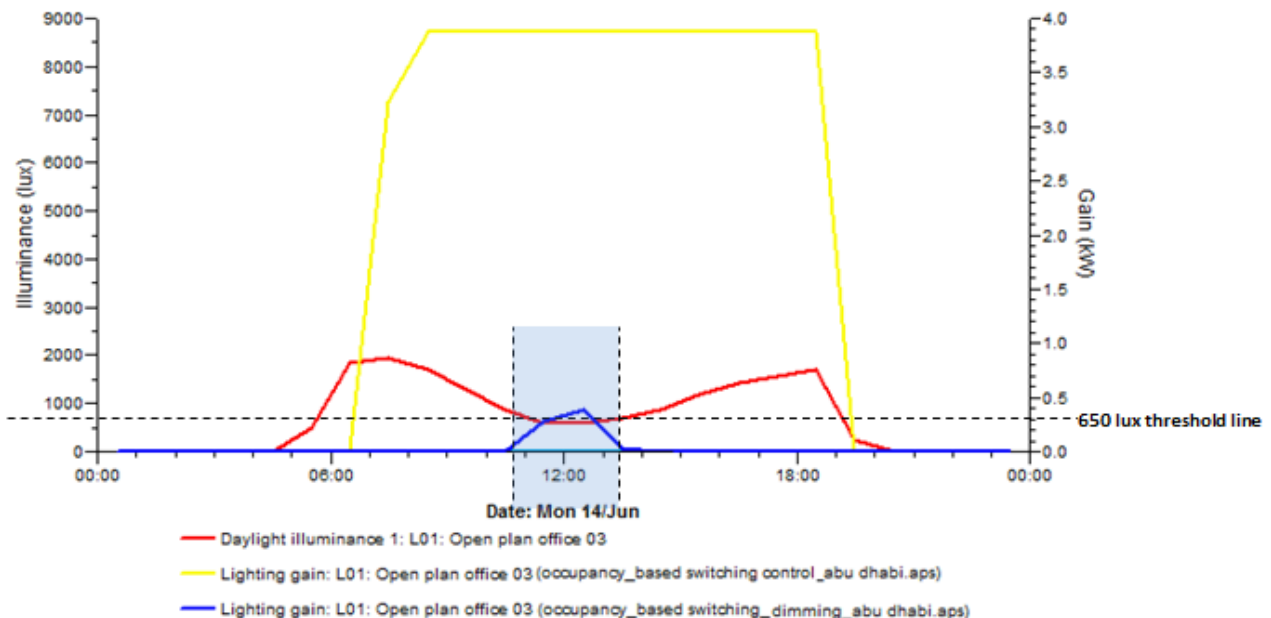

Figure 5-27 Comparison of daily lighting gains with and without the dimming control with the internal illuminance
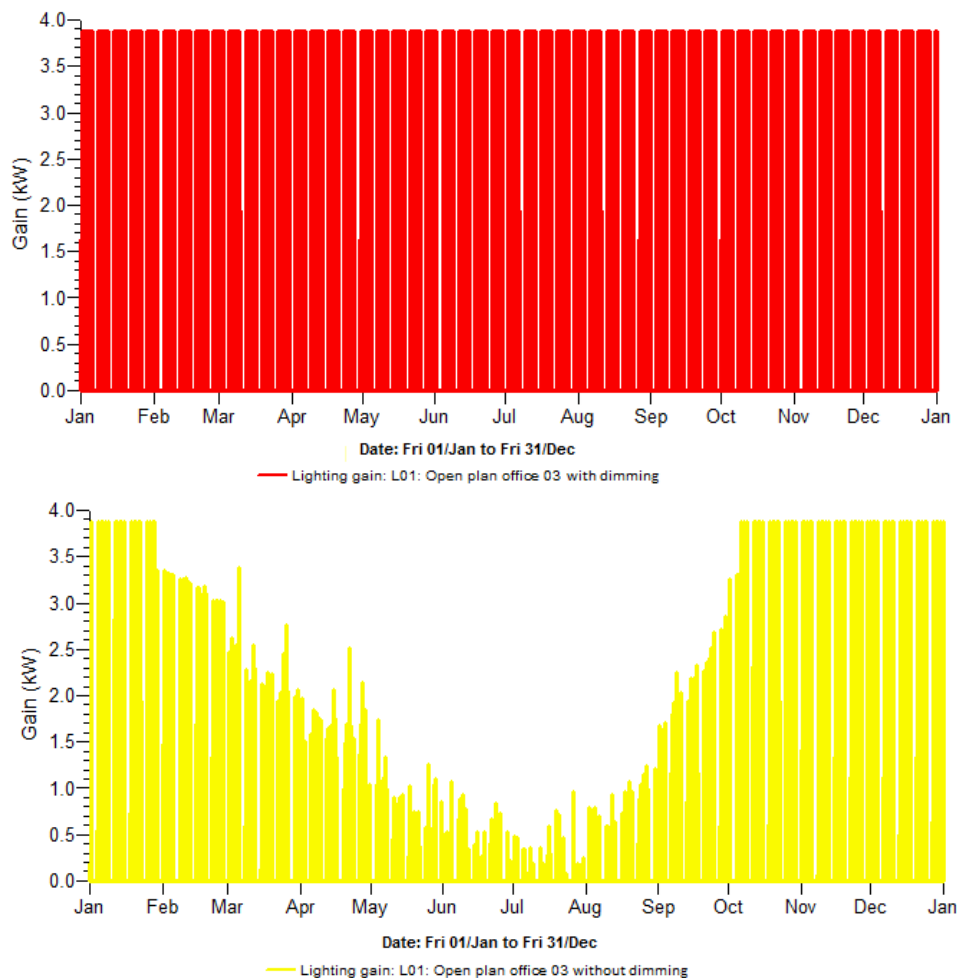
Figure 5-28 Comparison of annual internal gains between with and without the dimming control

6.   Conclusions

A range of shading control strategies and lighting control strategies were investigated in this study, which included manual lighting control, occupancy based switching control, occupancy based switching & daylight dimming control, static manual blind control, dynamic manual blind control, automated timed based blind control and the integrated dynamic shading & lighting control. The impact of these control strategies on the building energy performance was quantified individually based on a seven-storey office building model using advanced dynamic simulation tool IES <VE>.

Based on the simulation results it has indicated that by introducing shading devices it generally reduces the incoming solar gains of the perimeter spaces, which leads to a decrease in the cooling load and an increase in the heating load. Whether the total energy consumption can be reduced or not it mainly depends on the trade-off between the reduced cooling load and the increased heating load. In this sense, the type of shading control and the local climatic condition plays a key role. For climatic locations such as Singapore, it experiences an extensive cooling period over the year and has no heating requirement based on the office building model, therefore it is sensible to try to reduce the solar gains for the whole year. It has been shown that the total energy consumption was reduced by 2.6% by simply applying the static manual blind control which manually lowers the blinds during the occupied period. In contrast, for locations such as Beijing which has a hot summer and a cold winter, the blind control strategy needs to consider gaining the benefit from the solar gains for winter season. Hence, by simply applying the static manual blind control to Beijing it increased the total energy consumption.

It is also noted that the automated time based blind control was the only attempt which successfully achieved energy savings across all the selected climatic locations and it has more impact on warmer climates with less heating demand. As expected, Abu Dhabi and Singapore achieved the most energy reductions by 6.94 kWh/m^2 and 6.76 kWh/m^2 respectively whilst Beijing only received a slight energy reduction of 0.0609 kWh/m^2. As a result, it can be concluded that the time based switching control is the most energy efficient approach in all the examined shading control strategies and it does consider minimising the solar gains in the cooling mode and maximising the solar gains in the heating mode. To be able to maximise the benefit from employing the automated blind control for a climate with a hot summer and a cold winter such as Beijing, it suggests designing a further fine-tuned control strategy to tailor the local weather conditions, such as changes in the threshold of the external illuminance level or the definition of the heating and cooling modes (set point).

It is worth mentioning that the blind fabrics which were used for the examined shading controls were chosen to represent the average one of the current market with the consideration of visual comfort. This implies a potential to obtaining larger energy savings by swopping to a blind fabric with better Sthermal performance.

The simulation results have also shown that by applying the lighting control strategies it would generally reduce the lighting energy and the cooling load but increase the heating load, therefore whether there would be any energy saving achieved it all depends on the trade-off between the cooling, heating and lighting energy consumptions. It is interesting to note that the total energy consumption was increased up to 1.3% for all the five climatic locations when introducing the occupancy based switching control. This is due to the settings of the manual lighting control adopted in this study. As well known, the manual lighting control is the most common practice and also is the most un-predictive operation as it is largely determined by the individual preference and by whether a space is actually occupied or un-occupied. Over the past it has been commonly estimated with a large margin to represent the worst scenario. However the study has taken an optimistic approach to illustrate a scenario of the manual lighting control which is not extremely energy intensive. As a result, the occupancy based switching control consumed more lighting energy than the manual lighting control.

As expected, the occupancy based switching & daylight dimming control has proved to be the most efficient approach, which reduced the cooling load in a range between 3.6% and 13% and the total energy consumption from 2.7 % to nearly 5.0%. Once again, the climatic locations affect the extent of the energy reduction that can be achieved.

Finally, the main focus of the paper was attempted to understand the Somfy - Philips 'light balancing' system and to examine its potential impact on energy savings. This has been undertaken with a certain assumptions and simplifications and represented as the integrated dynamic shading and lighting control in this case study. Note that the integrated dynamic shading and lighting control was modelled as a combination of two separate controls, namely automated time-based blind control and occupancy based switching & daylight dimming control. Therefore, it requires a further research to be conducted to achieve the real integrated operation. In this context, the integrated dynamic shading and lighting control model still achieved up to 8% reduction in the total energy consumption in comparison with the baseline model in which there was no blind installed and the lighting was simply manually operated. Note that the predicted energy reductions were only indications based on the setup of the case study and the energy saving can be genuinely increased if a better blind fabric is chosen, a better floor layout is designed or different control thresholds are selected.

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## Appendix A: Specification of internal blinds

Table A-1 Specifications of interior roller blind and interior venetian blind

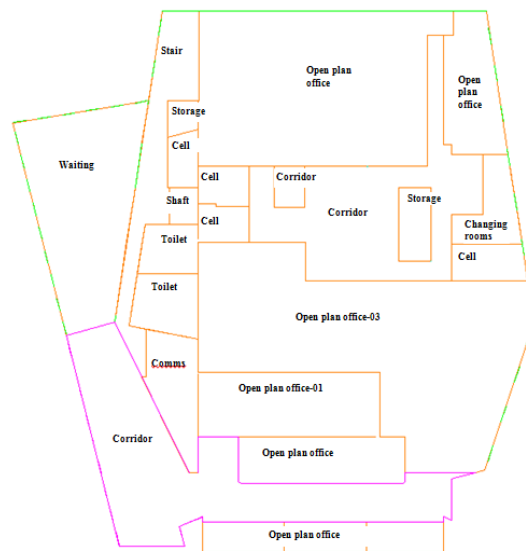|	Interior Roller Blind	Interior Venetian Blind
Thickness (m)	0.005	0.00024
Thermal conductivity (W/m·K)	0.1	0.9
Shading coefficient	0.3	0.61
Short-wave radiant fraction	0.3	0.61

Appendix B: Input data of the office building model
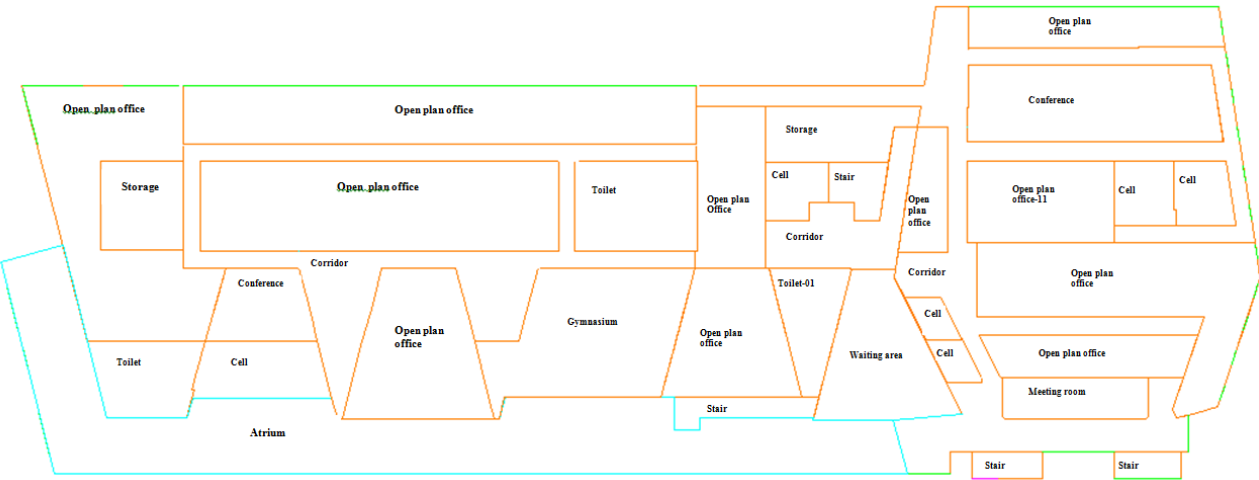
(a) Plan of ground and 1st floors
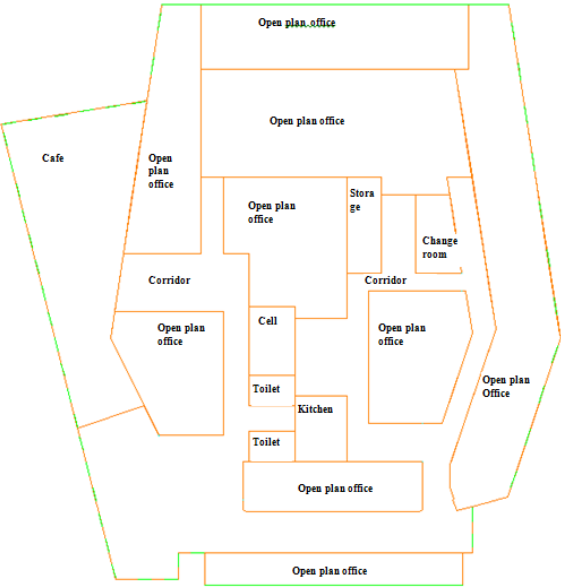
(b) Plan of 2nd and 3rd floors

(c) Plan of 4th, 5th and 6th floors

Figure 34 Plans of the office building model

Table B-1 Description of constructions used in case study model

Construction	Description	U-Value (W/m²K)
External wall	100m external brick 85mm Dense EPS Slab insulation 100m Concrete block 15mm Gypsum plastering	0.255
Internal partition	13mm Plaster 105mm brick 13mm plaster	1.6896
Ground Floor	250mm external brick 100mm cast concrete slab 63.5mm Dense EPS Slab insulation 25mm Chipboard 10mm Synthetic carpet	0.2499
Internal Floor/ceiling	75mm screed 200mm cast concrete (dense)	2.28
Internal ceiling finish	12.5mm Gypsum/plaster board	3.59
Roof	10mm Stone Chippings 5mm Felt/Bitumen layers 150mm cast concrete 150mm Glass-Fibre Quilt 100mm cavity 10mm ceiling tiles	0.20
External Glazing	6mm Pilkington (uncoated) 12mm cavity 6mm Pilkington (uncoated)	1.78 (g-value(EN410):0.641) (visible light transmittance: 0.76)
Spandrel Panel	20mm Plywood board 80mm mineral fibre slab 100mm concrete block 20mm Gypsum plasterboard	0.24
External door	40mm wood (Pine)	2.19

Table B-2 Internal gains of the office building model

| Space type | Lighting gain (w/m²) | Occupancy gain | | | Equipment gain (w/m²) |
		Max sensible gain (w/person)	Max latent gain (w/person)	Occupancy Density (m²/person)	
Cafe	7.8	67.11	42.9	3.46	14.72
Cellular office	15.0	73	50	9.00	11.68
Changing room	5.2	70	70	10.00	5.00
Circulation area	5.2	70	70	8.50	1.85
Common room	7.5	90	90	9.09	52.50
Conference room	5.2	73	50	9.00	11.77
Gym	7.8	102	198	6.07	15.00
Kitchen	26	63	117	9.26	42.22
Open plan office	15.0	73	50	9.00	11.68
Plant	7.5	90	90	9.09	52.50
Storage	1.88	70	70	8.08	0
Toilet	10.4	70	70	8.89	5.48
Waiting area	5.2	70	70	8.50	1.85

Table B-3 HVAC systems in the office building model

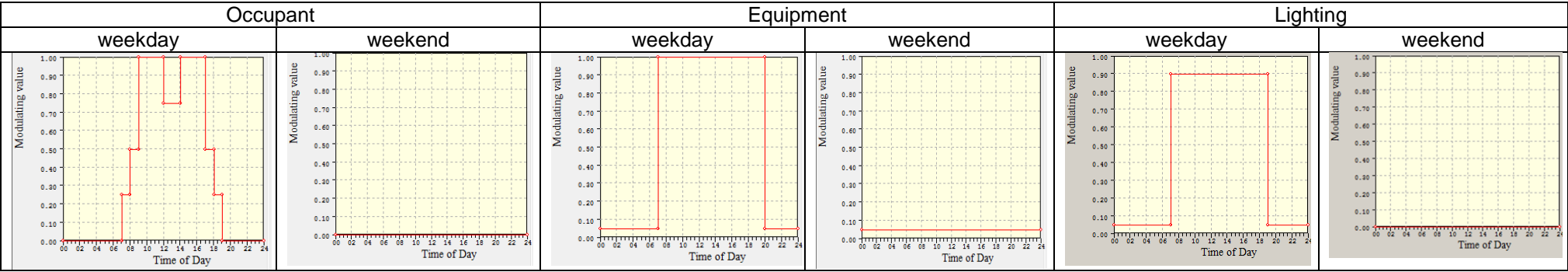| Spaces	HVAC system
Circulation	LTHW heating & natural ventilation
Open plan office	Fan Coil Unit
Waiting	Fan Coil Unit
Toilet	LTHW heating & mechanical ventilation extract mode
Cellular Office	Fan Coil Unit
Meeting room	Fan Coil Unit
Cafe	Fan Coil Unit
Kitchen	LTHW heating & mechanical ventilation
Gymnasium	Fan Coil Unit
Changing room	LTHW heating & mechanical ventilation extract mode
Storage	LTHW heating & mechanical ventilation

Table B-4 Heating and cooling set points and ventilation rates of the HVAC systems

| Spaces | Heating set point (°C) | | | Cooling set point (°C) | | | Ventilation rate (Nat. or Mach.) (l/s/person) |
| | Weekday | | | Weekday | | | |
	Occupied period	Un-occupied period	Weekend	2h (pre cooling)+ occupied period	Un-occupied	Weekend	
Circulation	20	12	12	N/A	N/A	N/A	10
Open plan office	22	12	12	24	N/A	N/A	10
Waiting	20	12	12	24	N/A	N/A	10
Toilet	20	12	12	N/A	N/A	N/A	12
Cellular Office	22	12	12	24	N/A	N/A	10
Meeting room	22	12	12	24	N/A	N/A	10
Cafe	23	12	12	24	N/A	N/A	10
Kitchen	17	12	12	N/A	N/A	N/A	25
Gymnasium	18	12	12	24	N/A	N/A	30
Changing room	22	12	12	N/A	N/A	N/A	10
Storage	20	12	12	N/A	N/A	N/A	10

Café

Occupant		Equipment		Lighting	
weekday	weekend	weekday	weekend	weekday	weekend
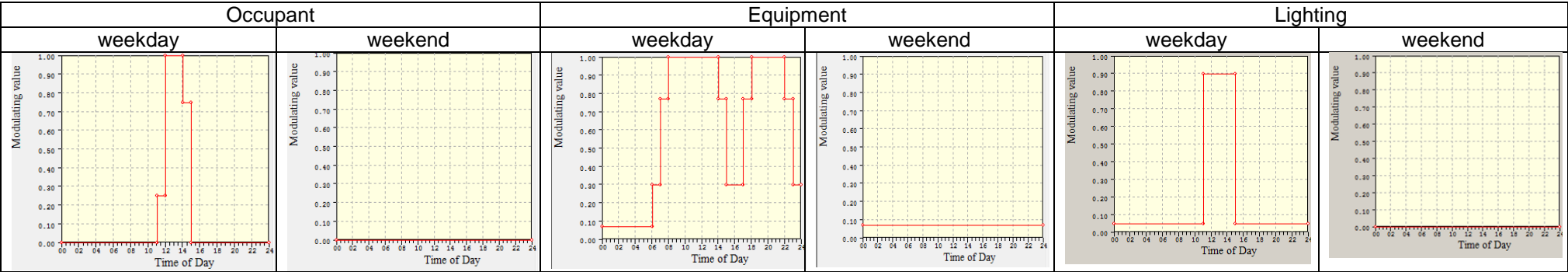
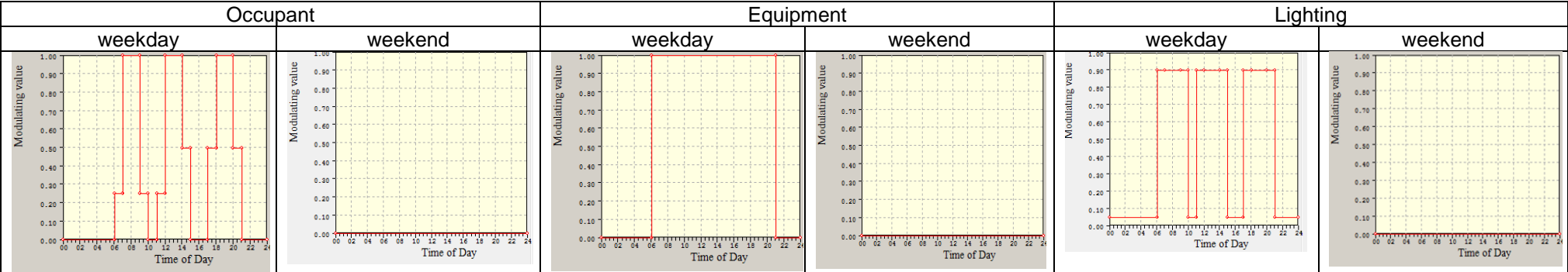*Cellular office/Open plan office/ Conference & meeting rooms/Common rooms*

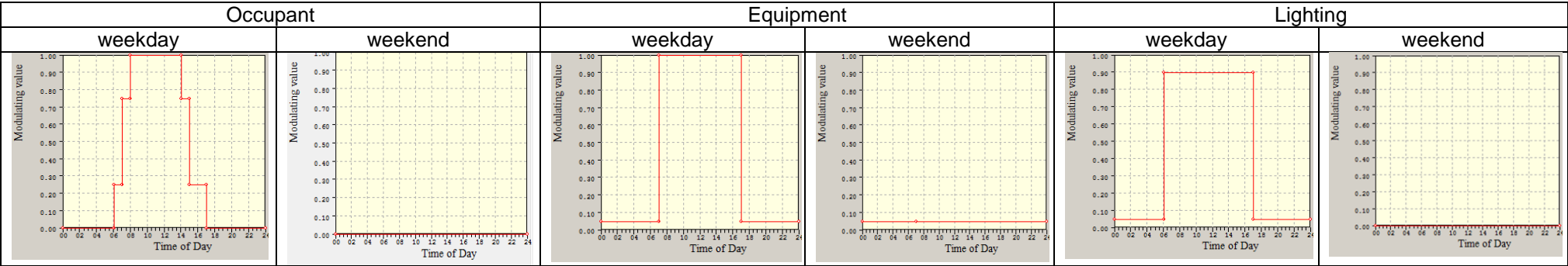| Occupant		Equipment		Lighting	
weekday	weekend	weekday	weekend	weekday	weekend

Changing room

Occupant		Equipment		Lighting	
weekday	weekend	weekday	weekend	weekday	weekend

Circulation

Occupant		Equipment		Lighting	
weekday	weekend	weekday	weekend	weekday	weekend

Gym

Occupant		Equipment		Lighting	
weekday	weekend	weekday	weekend	weekday	weekend

Kitchen

Occupant		Equipment		Lighting	
weekday	weekend	weekday	weekend	weekday	weekend

Storage
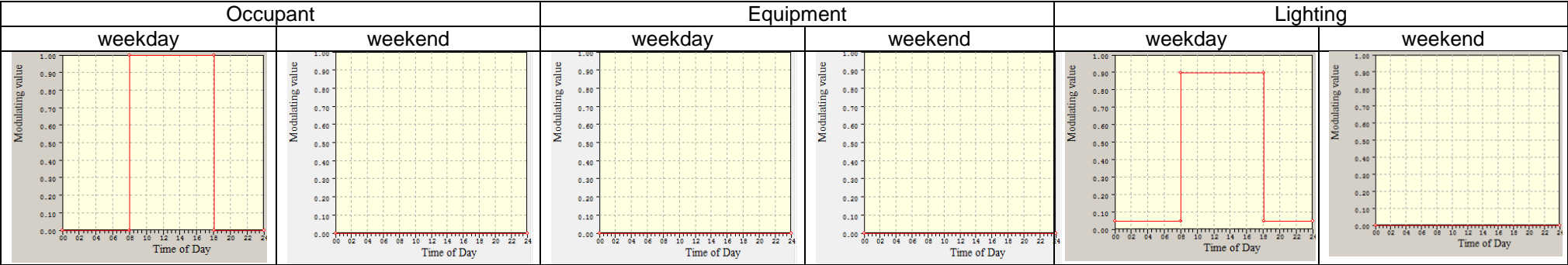
Toilet

Waiting
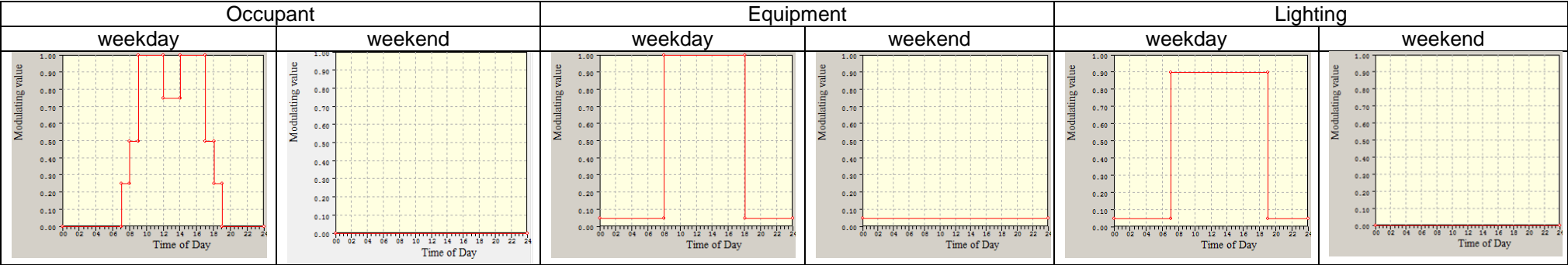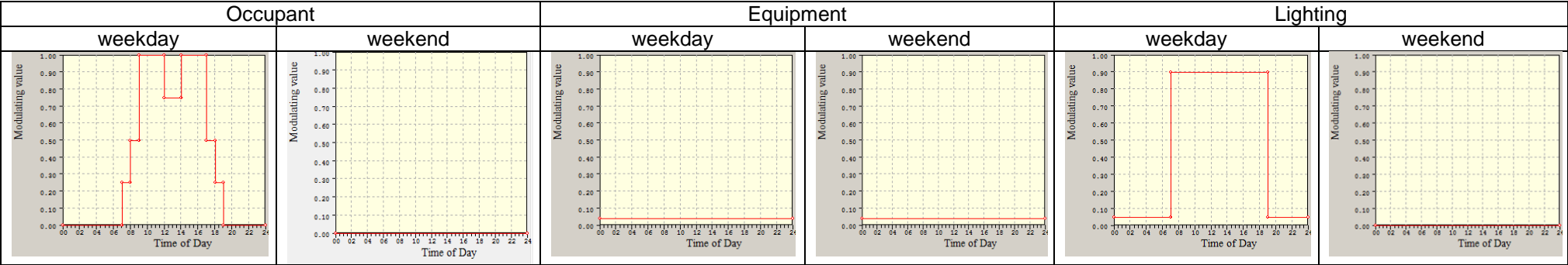

Figure 35 Schedule profiles of internal gains for the baseline model