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An Evaluation of the Potential Energy Benefits of Installing Green Roofs in Hong Kong

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AN EVALUATION OF THE POTENTIAL ENERGY BENEFITS OF INSTALLING GREEN ROOFS IN HONG KONG

by

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Abstract

Green roofs help mitigate the urban heat island effect, increase available green space, and reduce energy consumption of buildings. This thesis estimates potential energy benefits of installing green roofs on buildings in Hong Kong. EnergyPlus, a building energy simulation program, is used to model an extensive green roof installed on a two-storey building in downtown Hong Kong. Indoor and outdoor temperature data were collected from the green roof. Model calibration is performed using monitoring data, meeting the set acceptable margin of error of ± 20%. Air conditioning usage from April to September is approximately 232 kWh less in the room under the green roof than for the original roof showing that green roofs can reduce heat flux from the roof into buildings. Compared to other energy saving technologies, the cool roof provides a savings of 184 kWh over the green roof, translating to a $55 annual reduction in energy costs.

Acknowledgements

I would like to acknowledge the help and guidance of Dr. James Li throughout the duration of this work. His insight and patience were very much appreciated. I would also like to thank Kristen Hahn who worked on the Oi Kwan green roof case study.

I would especially like to thank my family. Without their support this milestone would not be complete. My father and brother provided their expertise in Microsoft Excel and insights into problem solving, and mother provided her genuine interest. Most of all, I would like to thank my husband, Jonathan, for his ongoing encouragement, moral support, advice, and proficiency in the English language. Thank you to my son, Adin, for his precious smile.

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Acronyms and Abbreviations

BLAST	Building Loads Analysis and System Thermodynamics
CBA	Cost benefit analysis
CRRC	Cool Roof Rating Council
CSMC	Chun Seen Mei Chuen
DOE	Department of Energy
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau
HKHS	Hong Kong Housing Society
HKPU	Hong Kong Polytechnic University
HVAC	Heating, ventilation, and air conditioning
LAI	Leaf area index
PVC	Polyvinyl chloride
RTTV	Roof thermal transfer value
U.S.	United States

Chapter 1 – Introduction

Green technologies provide a way to increase the energy efficiency of buildings with respect to the use of resources such as energy, water, and materials. Using green technologies helps reduce the impact of a building on human health and the environment. By taking into account the entire lifecycle of a building during the design process, the consumption of these key resources can be significantly reduced (United States Environmental Protection Agency, 2009). Installing a green roof is one way of moving towards a greener building. Considering the increasing energy needs worldwide, it is a good idea to install green roofs in order to reduce the heating and cooling load on buildings.

Some examples of the benefits of implementing green roofs instead of standard roofs are improved urban air quality (Tan & Sia, 2005), reduced storm water runoff (Jennings, Hunt, & Moran, 2003), reduced energy consumption of buildings (Kohler, 2002), and reduced effects of the urban heat island effect (Akbari, 2001). The urban heat island effect is the concept that the temperature in urban environments, where there is a high concentration of tall buildings, is often higher than in more rural areas. Tall buildings tend to trap solar radiation, creating a micro-climate. Green roof vegetation and soil substrate can absorb and reflect radiation, reducing the heat that would normally be trapped by conventional roofs during warm weather. Green roofs may also have social benefits such as promotion of health and well-being, creation of an open space, improved aesthetics and available green space, and therapeutic benefits (City of Toronto & OCE-ETech, 2005).

Hong Kong is a region that could benefit from wide-scale implementation of green roofs. Hong Kong is a highly urbanized city with minimal green space and a population of over seven million people (Information Services Department, 2009). Green roofs would be beneficial in reducing the urban heat island effect, providing more energy efficient buildings, and increasing the amount of visible green space, particularly for low-rise buildings. Data from the Hong Kong Observatory show that temperature in urban areas of Hong Kong is increasing at a rate of 0.6°C per decade, which is much higher than in more rural areas where the temperature is increasing at a rate of 0.2°C per decade (Townshend, 2007).

The feasibility and applicability of installing green roofs in Hong Kong is dependent on building type. Installing green roofs in the Old City Centre may not be practical because of very tall and narrow high-rise buildings with little roof space. Additionally, the energy benefits from green roofs will not be as pronounced on high-rise buildings that are 10 to 50 storeys as they will be on low-rise buildings. Although the aesthetic benefits of intensive green roofs in Hong Kong have been the focus for promoting green roofs (Townshend, 2007), extensive green roofs would benefit low-rise buildings the most because of greater affordability coupled with tangible energy savings.

1.1 Objective and Scope

The main objective of this thesis is to investigate and estimate the potential energy benefits of installing green roofs on buildings in Hong Kong. The scope is limited to extensive green roofs on low-rise buildings in Hong Kong. The scope also includes investigating the energy benefits of alternative green technologies such as a cool roof, added roof insulation, and reflective windows.

1.2 Methodology Overview

The objective of this thesis will be met by:

- analyzing the potential energy benefit of green roofs using field monitoring data from a low-rise building in Hong Kong;
- modelling a two-storey building in downtown Hong Kong, operated by the Hong Kong Housing Society, with an extensive green roof, using EnergyPlus, a building energy simulation model;
- comparing monitored indoor and outdoor temperature data collected from the site against predicted temperature data from the EnergyPlus model;
- predicting energy and cost savings from the green roof over a conventional roof;
- comparing temperature, energy, and cost savings from using a green roof to alternatives; and
- providing recommendations on the most viable option for reducing energy consumption of buildings in Hong Kong.

It is predicted that using a green roof will reduce roof surface and indoor air temperatures, reduce the heat flux into the building, and reduce the cost of operating the building, especially during the summer months. The full methodology is presented in Chapter 4.

Chapter 2 – Literature Review

2.1 Green Roof Background

A green roof is a layer of vegetation placed or planted on a roof. A typical green roof consists of a structural support layer on the bottom, followed by a waterproof roofing membrane, insulation, and a drainage layer and root barrier, followed by growing medium such as soil and vegetation, as shown in Figure 2.1. Green roof guidelines published in 2002 by the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL), a landscape industry organization in Germany, are the basis for design of most green roofs built today. These guidelines focus on the planning, execution, and upkeep of green roofs.

Figure 2.1: Typical Layers in a Green Roof (City of Toronto, 2010)

There are two main types of green roofs: intensive and extensive (Peck & Callaghan, 1999). Intensive green roofs require the most maintenance and watering, are typically accessible to visitors, and are usually very aesthetically pleasing because of the variety of trees, shrubs, and grass used for vegetation. However, intensive green roofs are more expensive than extensive green roofs, require high technical expertise for construction, place a large load on the roof, and usually require a deep growing medium to support the landscape. Extensive green roofs are a more passive alternative to intensive roofs and also require much less maintenance. The vegetation used creates a natural landscape, where the plants can grow freely. It is important that the plants selected be able to handle extreme weather conditions. Extensive green roofs are a good choice for retrofit buildings, are inexpensive compared to the intensive option, and only require a shallow growing medium. However, extensive green roofs can be unattractive and also have limited vegetation options (Peck & Callaghan, 1999). Table 2.1 presents a summary of the advantages and disadvantages of intensive and extensive green roofs.

Table 2.1: Summary of Advantages and Disadvantages of Extensive and Intensive Green Roofs (Peck & Callaghan, 1999)

Extensive	Intensive
Advantages	
Lightweight	Large plant diversity
Low maintenance	Attractive
Good for retrofit	Usually accessible
Good for 0-30° slope	Can grow food
Inexpensive	
Low technical knowledge	
Disadvantages	
Limited plant choice	More expensive
Can be unattractive	High technical expertise
	High roof load
	Need for irrigation/drainage

Various options for green roof design exist as well. Green roofs can be purchased as complete green roof systems, as modular systems or as pre-cultivated vegetation blankets. A brief overview of some of the design options for green roofs is discussed here. Soprema, a Canadian construction and roofing company, sells the SOPRANATURE green roof system, which includes six versatile systems with different types of layers and vegetation (Soprema, 2009). Another type of system, the modular system, incorporates the drainage and filter layer[1], soil/substrate medium, and the

[1] The root barrier may be included in this layer.

vegetation into one system, usually on a lightweight high-density polyethylene module (Velazquez, 2003). The modules are then interlocked to provide full coverage. Some of the main benefits of using a modular system instead of the multi-layered design for green roofs are: easier and more time efficient installation, design simplification, and the ability for off-site planting. Because the module is prepared off-site it can be installed on the roof with minimal effort. Additionally, the plants can be grown off-site and as such can be grown at any time of the year and can also be installed on the roof at any time of the year because a plant and root foundation already exist. This helps improve the immediate aesthetic appearance of the roof. Since each module is separate, each module can have different substrate and soil mixtures and depths depending on the needs of the plant. This contributes to greater vegetation diversification on the rooftop.

Another option is pre-cultivated vegetation blankets, which can be placed directly on the roof and require watering only for the first few weeks (Xeroflor Canada, 2008). Many vegetation mats are certified to be wind-uplift resistant, fire resistant, erosion resistant, and are designed to prevent many types of weeds from growing. A general green roof system would have a root barrier, made of low-density polyethylene, laid out directly on the roof, then the drainage layer, followed by the moisture retention fleece and then the moss-sedum vegetation mat. The water retention fleece is usually made from polymeric fiber and should retain nutrients for the plants, increasing the water retention capacity of the roof and reducing the amount of water going to the storm water runoff. Routine maintenance may be required for the green roof systems such as fertilizer application about twice a year and irrigation if there is extreme drought.

(Xeroflor Canada, n.d.). Green roofs can also be customized for individual buildings, which was the case for the green roofs discussed in this thesis.

2.2 Energy Balance

The energy balance of a green roof can be described in terms of its incoming and outgoing energy. Solar radiation is the main source of incoming energy that impacts on any roof type, green roofs included. Incoming solar radiation can be divided into short-wave radiation and long-wave radiation (emitted in the form of thermal infrared); however, the majority of incoming radiation is short-wave. Short-wave radiation that is not absorbed by the Earth's surface is reflected and absorbed by objects such as clouds and then re-emitted to the Earth's surface as long-wave radiation. Incoming solar energy is balanced by sensible heat, latent heat, and stored heat. Sensible heat is released back into the atmosphere through convection when soil surface energy is greater than the atmosphere. Latent heat results from evapotranspiration – evaporation from the soil surface and transpiration through the plants. Stored heat is the remaining heat that is stored by the green roof substrate and either releases back into the atmosphere at night or enters the building (Sailor, 2008). Overall, the energy balance of a green roof can be described according to the following equation (Tsang & Jim, 2011):

$$K_i + K_r + L_i + L_r = Q_E + Q_H + Q_S$$

where,

K_i = incident short-wave radiation
K_r = reflected short-wave radiation
L_i = incident long-wave radiation
L_r = reflected long-wave radiation
Q_E = latent heat
Q_H = sensible heat
Q_S = stored heat

2.3 Summary of Literature on Green Roofs

The majority of green roof research has been conducted in parts of Europe and North America. Green roofs have been used in Germany since the 1980s and their popularity has grown tremendously. In 1989, green roofs covered 1 million square metres of roofs in Germany, and by 1996 green roofs covered over 10 million square metres. The main reason there was such a large growth was because of municipal grants and state legislation that provided funding for green roof construction (Peck & Callaghan, 1999). Since these initiatives in Germany, other European countries and cities have passed municipal by-laws requiring green roofs on certain buildings and providing funding during different stages of the green roof's lifespan. As a result, green roofs are much more common in France, Austria, Norway, Switzerland, and Germany than in areas without these initiatives.

As discussed in Chapter 1, there are numerous benefits to installing green roofs on buildings such as reduction in the urban heat island effect, reduction in storm water runoff, and improvement of air quality; however, this thesis focuses on energy benefits. The survey of existing literature focuses on these energy benefits. Palomo Del Barrio

(1997) developed a model to analyze the cooling potential of green roofs in Southern Europe during the summer months only. This model showed how green roofs can be used for building insulation. The green roof model combined together the support model, soil model, and canopy model to determine the effect of heat flux through the roof for particular design parameters of soil thickness, density, and moisture, and canopy transpiration. The results of the model showed that increasing soil thickness decreased the heat flux into the building. Similarly, increasing the soil moisture reduced the heat flux into the building. However, decreasing the soil density reduced the heat flux into the building. Varying canopy transpiration had little effect on heat flux. However, using plants with a lot of foliage and with a majority of the leaves distributed horizontally can reduce the solar radiation transmission and provide good shadowing for the roof, providing more insulation.

In Germany, Kohler (2002) compared a gravel-covered roof in Neubrandenburg and a bitumen-sealed roof in Berlin to green roofs at the corresponding locations. The gravel roof had similar temperature results to the green roof, although added a heavier load to the building. The bitumen roof surface temperature was about 10ºC warmer than the green roof. Liu & Minor (2005) also studied the effect of green roofs on surface temperature reduction and heat flow through the roof on installation green roofs in Toronto. The green roofs reduced the summer temperature of the roof by more than 20ºC and reduced the heat flux through the roof by 70 to 90 percent. Results were not as significant in the winter because the soil substrate froze, but the heat flux into the building decreased by about 10 to 30 percent.

A life cycle assessment conducted on a multi-storey residential building in Madrid compared the environmental impacts of buildings with and without green roofs (Saiz, Kennedy, Bass, & Pressnail, 2006). Roofs in Madrid are typically composed of a PVC membrane on the bottom followed by 'filtron tiles' made of 4 cm extruded polystyrene insulation and a layer of gray gravel on top for protection. Saiz et al. (2006) compared a regular gray gravel roof, a regular roof with a white reflective paint coating, and an extensive green roof. The extensive green roof had a 9-cm soil substrate layer with a vegetation layer of sedum, cactus, and desert shrub, plants common to extensive green roofs in Madrid climate. These plants are known to be drought resistant and do not require high maintenance. One of the major benefits of a green roof is its low solar absorption resulting in lower roof surface temperatures and therefore a reduction in heat flux into the building. In this case, the maximum temperature of the regular roof was 65ºC, the white roof 42ºC, and the green roof 35ºC. This resulted in a reduction of 1.2 percent in the annual energy use of the building, with a greater reduction in the summer than in the winter. It is important to note that the green roof was only added to 16 percent of the available roof surface. The study showed similar benefits in summer cooling between the green roof and the white roof (the white roof achieved approximately 65 percent of the energy savings of the green roof); however, these reductions did not exist in the winter from the white roof (Saiz et al., 2006).

Fewer studies have been conducted in tropical climates where there are larger climatic extremes than those found in more temperate regions. Similar to Palomo Del Barrio (1997), Wong et al. (2003) found that in Singapore increasing the soil thickness reduced the heat transfer into the building. However, this correlation was more significant for dry clay soil than 40 percent moisture content clay soil. In this study, Wong et al. (2003) used the DOE-2 energy simulation model to explore the potential energy consumption reduction by installing a green roof on a hypothetical five-storey commercial building in Singapore. Specifically, the study investigated the use of green roofs to decrease heat transfer into the building, reduce energy consumption (which can translate into cost savings), and optimize the roof thermal transfer value (RTTV, also known as R-value). In order to meet the objectives a comparison was conducted on three hypothetical roof types: exposed roof, typical flat roof, and a green roof (on both exposed and typical roofs). The vegetation types for the green roof were turfing, shrubs and trees. The difference between the exposed roof and the typical flat roof is that the exposed roof is a typical concrete roof whereas the typical flat roof includes the filter, drainage, protection, and root membrane layers characteristic of most green roofs. Data from a green roof on a low-rise building in Singapore were used to estimate the R-value for input into the model. The results of the model showed that adding vegetation to the roofs reduced the heat transfer through the roof and into the building. The greatest reduction – about 15 percent less energy consumption – occurred by putting shrubs on the exposed roof. This translated to a cost savings of US$3625 per year. Shrubs also showed 81 percent reduction in peak RTTV. Shrubs have a higher leaf-area index (LAI) than turfing and trees, which explains the more significant results compared to other vegetation types. Adding vegetation to the typical flat roof was also beneficial, but the savings were not as significant as those for the exposed roof.

Another study conducted in Singapore evaluated the benefits of using a green roof to reduce surface and ambient air temperature and improve air quality (Tan & Sia, 2005). Four types of green roofs were installed on the roof of a multi storey carpark, and each was required to meet 1.5 kN/m^2, the maximum structural loading capacity. In order to evaluate the environmental benefits of the green roofs, pre-installation data were compared with post-installation data. The surface temperature of the roof was measured over a period of two months before the installation of the green roofs. After the green roofs were installed the soil temperature and surface temperature of the roof was measured over a period of 12 months. The surface temperature of the green roof was 15ºC to 20ºC cooler than the regular concrete roof. However, after there was no rain for two to three weeks, the soil/substrate temperature (peak temperature 73.4ºC) was higher than the temperature of the original roof. The ambient air temperature at 300 mm and 1200 mm above the roof surface was also measured before and after installation. The ambient air temperature was between 1.7ºC and 3ºC lower with the green roof than with the original roof.

Recent green roof research was performed in the subtropical climate of Austin Texas (Simmons, Gardiner, Windhager, & Tinsley, 2008). Surface temperature data were collected from a black roof, a white roof, and multiple green roofs. The black and white roof temperature reached 68ºC and 42ºC respectively whereas the temperature of the green roofs was in the range of 31ºC to 38ºC. However, during cooler weather the temperature of the green roofs was warmer than the other roofs by about 2ºC to 5ºC. Simmons et al. (2008) concluded that there are many factors that contribute to the performance of the green roof. Two of the main factors are climate and design. It is difficult to extrapolate data from one area to determine success or failure of green roofs in another region. It is important to perform green roof experiments in unstudied regions in order to assess the viability of green roofs in many locations.

Currently, minimal green roof research has been performed in the subtropical city of Hong Kong. Hong Kong is a very densely populated city with a lot of traffic congestion, poor air quality, and little green space. Ambient temperatures range from approximately 16˚C in the winter to almost 30˚C in the summer (Hong Kong Observatory, 2010). Installing green roofs in Hong Kong can help mitigate the urban heat island effect, increase the amount of green space available, and reduce the energy consumption of buildings. Because of the lack of green space in Hong Kong, intensive green roofs, as attractive landscaping, have become quite popular (Townshend, 2007). However, extensive green roofs can be installed more widely and therefore can have greater overall benefits.

In 2002, an extensive modular green roof was installed on a sloping roof of an office building owned by Gammon-Skanska. Results from the study showed temperature reductions in the soil and ceiling underneath the green roof compared to a similar building without a green roof (Hui, 2006). Jim & Tsang (2011) studied the thermal effect of an experimental intensive green roof, constructed in 2008 on an electricity substation building in Hong Kong, with a 100 cm substrate layer and 5 m to 10 m of native trees. Results over all four seasons showed that the green roof reduced the heat flux into the building during all seasons except winter. During winter, heat loss from the substrate layer of the green roof occurred causing warm indoor air to penetrate outdoors.

A recent green roof study on the Oi Kwan Social Services Building in Wan Chai, Hong Kong was conducted in 2008 by K. Hahn, R. Parker, and Dr. J. Li in conjunction with the Hong Kong Polytechnic University. Results showed lower surface temperatures for the green roofs compared to the control roof (see Chapter 3 for more details); however, energy consumption comparisons were not quantified.

Overall, the literature shows that green roofs have the potential to reduce roof surface and indoor air temperature and reduce energy consumption of buildings. This thesis builds on other studies conducted in Hong Kong, but is the first study to investigate, using the EnergyPlus model, the potential energy benefits of installing green roofs on buildings in Hong Kong, and compare, using the EnergyPlus model, the energy performance of multiple alternatives to a green roof.

Chapter 3 – Experimental Green Roof Case Study at Oi Kwan

3.1 Background and Green Roof Installation

The Hong Kong Polytechnic University retained Ryerson University to assist with a demonstration green roof project at the Oi Kwan social services site in Wan Chai, Hong Kong, a typical building in an old district with high building density and underutilized roofs. The study was initiated to assess the benefits of installing extensive green roofs on older buildings in Hong Kong while minimizing the load on the roof (Hong Kong Polytechnic University, 2008).

The demonstration extensive green roof was constructed as a retrofit on the pre-existing concrete roof of a 9 storey, twenty-five year old building. The 55 m^2 green roof consisted of an aluminum frame with a plastic waterproof membrane to prevent water leakage, followed by a 10 mm thick egg crate layer made of filter fibre to prevent substrate erosion but to allow drainage, followed by a root barrier. The green roof was then subdivided into four sections with varying types of growing media and vegetation, as shown in Figure 3.1. When soil was used as the only substrate, the growing medium was 6 inches thick. When soil and rock wool were combined, the growing medium consisted of 2 inches of rock wool followed by 4 inches of soil on top. Rock wool consists of ground up lava rocks and is a good growing medium for vegetation because it is lighter and capable of retaining more water than soil. The adjacent pre-existing concrete roof was used as the control roof.

* Section 1 – grass with soil; Section 2 – grass and various plants with soil; Section 3 – grass with soil and rock wool; Section 4 – Grass and various plants with soil and rock wool.

Figure 3.1: Experimental Design of Subplots for Oi Kwan Green Roof

The study period was from July 31, 2007 to August 31, 2007; however, data are missing for sub-plots S3 and S4 for part of the study period. Data loggers recorded temperature readings at 20 minute intervals for the surface of each of the four sub-plots and the control roof surface, as well as the indoor air temperature for the rooms underlying each roof type. Each of the four sub-plots had a temperature logger installed at the soil surface, with electronic components housed in waterproof boxes. The same instrument was installed on the concrete roof surface as a control point and all loggers were wired back to a computer, housed in a weatherproof shelter. Calibration tests showed that the margin of error between all sensors was 0.5°C. Additionally, temperature loggers were installed on the soffit surface under the green roof and under the control roof to measure indoor temperatures of the ninth-floor rooms underlying each respective roof type.

3.2 Purpose

The purpose of the Oi Kwan green roof study was to investigate:

- the effect of different plants and growing media on roof surface temperature;
- the distribution of time where the maximum temperature is reached for each treatment option; and
- the effect of retrofit green roofs on underlying room temperature.

3.3 Data Analysis and Results

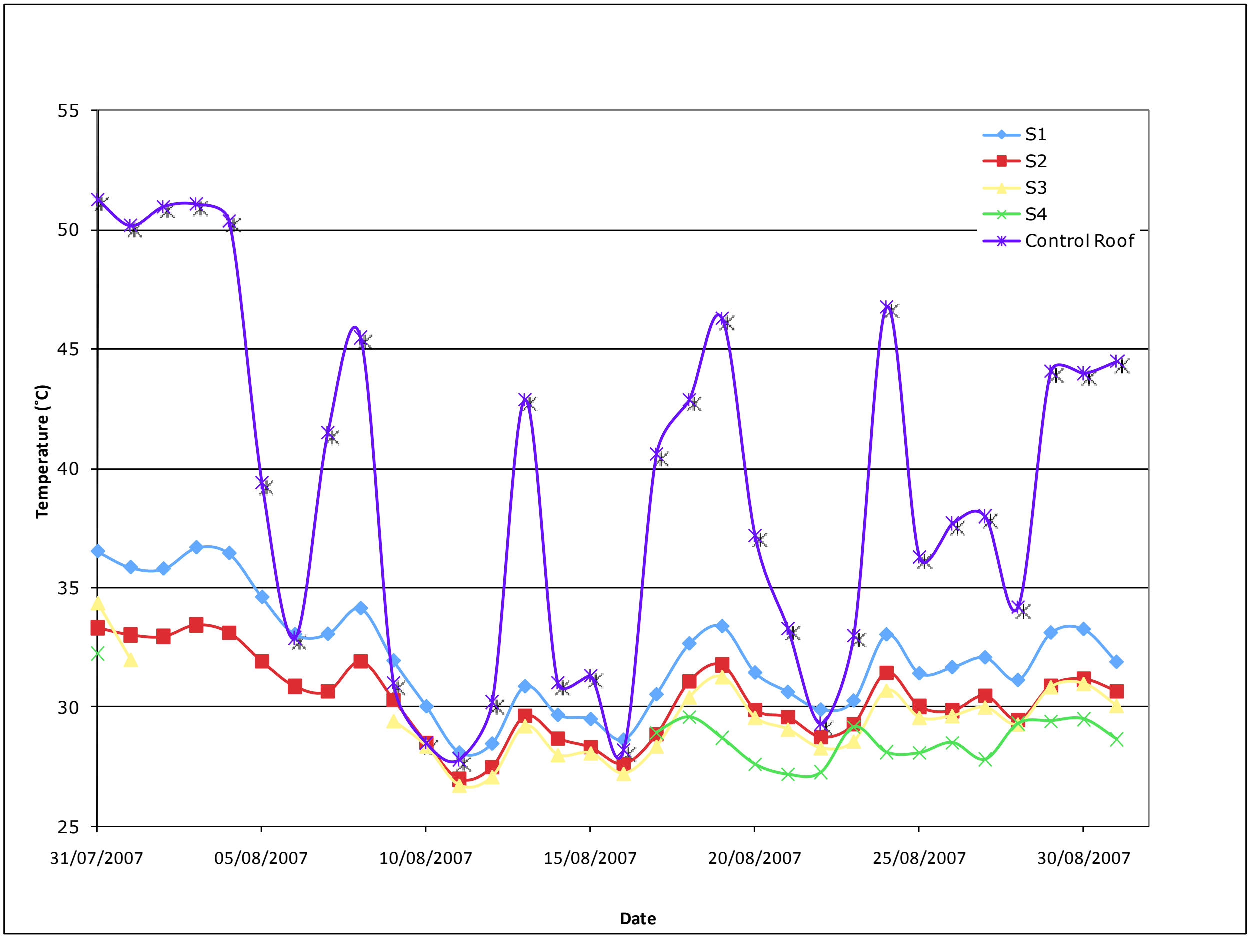
The data were analyzed by looking at the maximum daily temperature for each treatment over a 24 hour time period. The time at which the maximum daily temperature occurred was determined and plotted to examine differences between treatments. Temperature duration curves were created by calculating the frequency of occurrence of all temperature readings recorded throughout the study period occurring at or above various temperatures.

3.3.1 Roof Surface Temperature

Figure 3.2 shows the daily maximum surface temperature for the study period. For 26 days out of the 32-day observation period, the maximum daily temperature of the control roof exceeded that of all green roof treatments. The difference in maximum surface temperatures was greatest when ambient air temperature was also high. On 15 percent of the observation days, the control roof maximum daily temperature exceeded

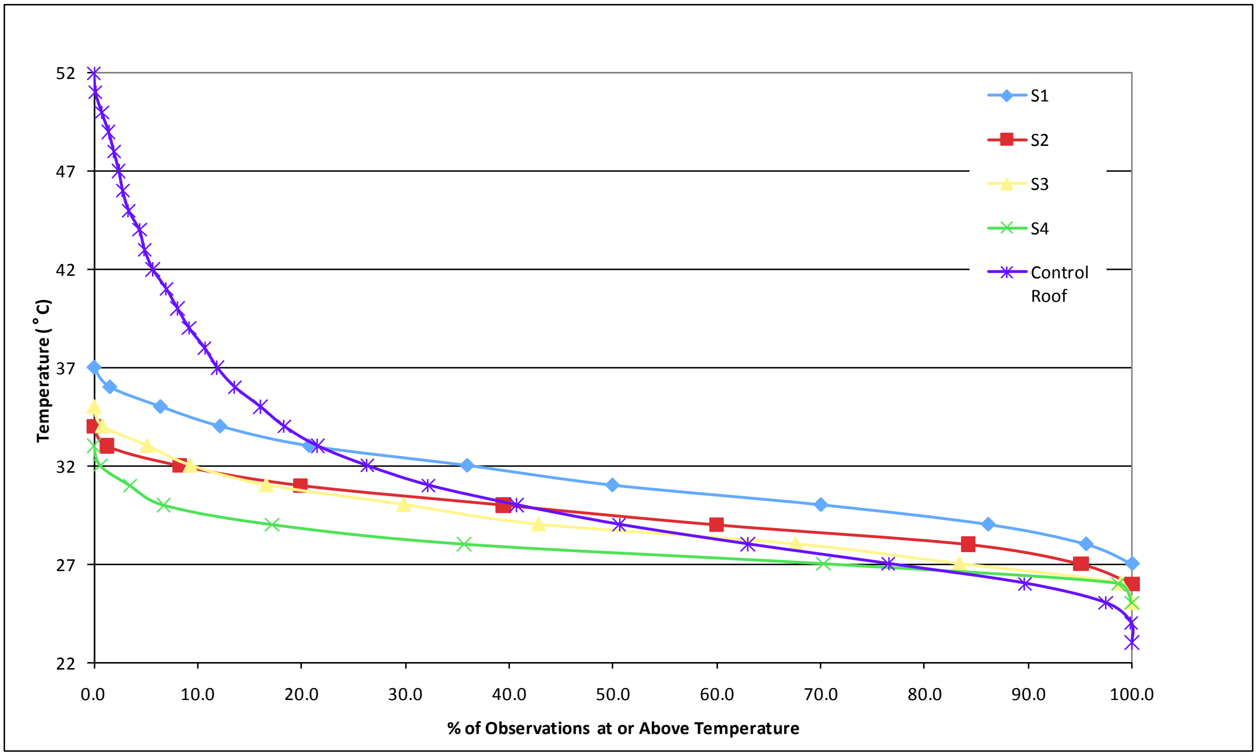
50˚C. On 46 percent of the observation days, the control roof maximum daily temperature exceeded 40˚C. Conversely, on all observation days, the maximum daily temperature for all green roof treatments remained below 37˚C. Figure 3.3 shows the temperature duration curve for the control roof and all green roof treatments. The control roof experienced temperature fluctuations between 21˚C and 51˚C, compared to the green roofs that experienced temperature fluctuations between 26˚C and 36˚C. Smaller temperature fluctuations on the green roof indicate that components of the green roof are subject to less thermal stress than the control roof, potentially contributing to greater roof longevity for the green roofs (Liu & Baskaran, 2004).

Between the four green roof treatments, Section S1 (grass and soil) generally experienced the highest maximum daily temperature. The maximum daily surface temperatures for Sections S2 (grass and mixed plants with soil) and S3 (grass with soil and rock wool) were approximately 2˚C cooler than for S1. Although data were missing for S3 and S4 (grass and mixed plants with soil and rock wool) for part of the study period (due to monitoring equipment malfunction), on 75 percent of the recorded observations, S4 experienced the coolest surface temperatures compared to the other green roof treatments. This suggests that a mixture of plants and including rock wool in the substrate layer may be the most effective green roof design for cooling purposes.



* S1 – grass with soil; S2 – grass and various mixed plants with soil; S3 – grass with soil and rock wool; S4 – grass and various mixed plants with soil and rock wool

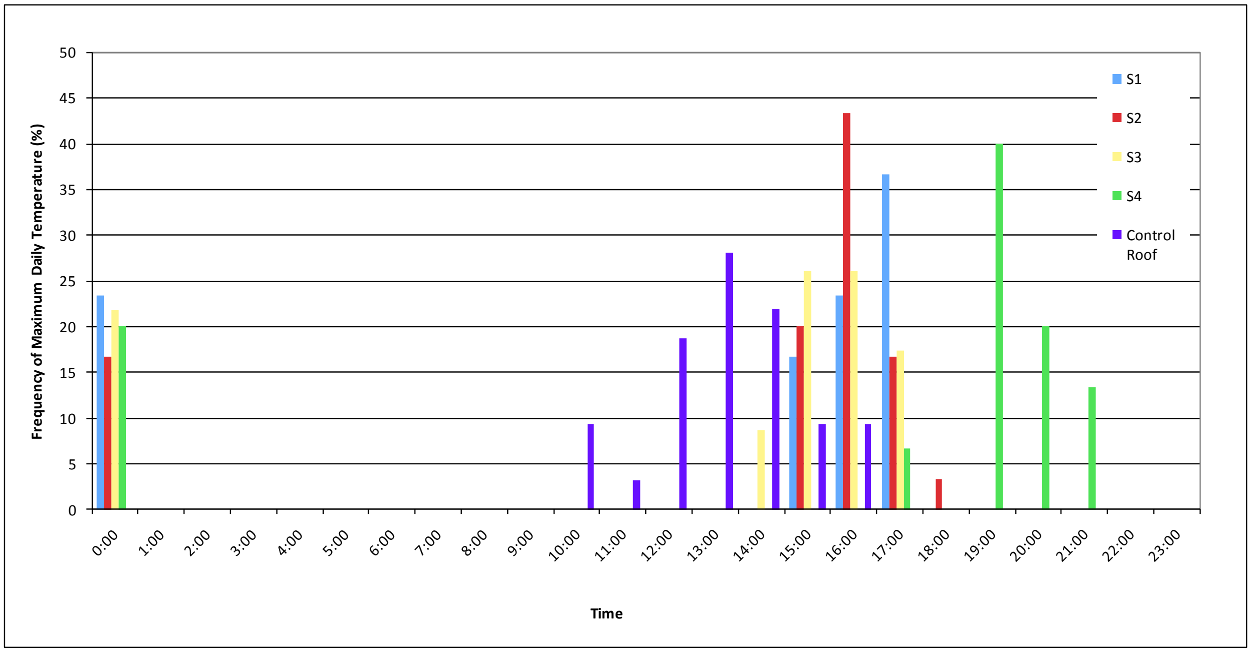
Figure 3.2: Daily Maximum Temperature of Control Roof and Various Green Roof Designs



* S1 – grass with soil; S2 – grass and various mixed plants with soil; S3 – grass with soil and rock wool; S4 – grass and various mixed plants with soil and rock wool

Figure 3.3: Temperature Duration Curves for Control Roof and Various Green Roof Designs

Figure 3.4 shows that approximately 70 percent of the time the control roof reached its maximum temperature between 12:00pm and 3:00pm. The time at which the green roofs reached their maximum temperatures was shifted to later in the day. S1, S2, and S3 reached their maximum temperatures between 3:00pm and 6:00pm 77 percent, 80 percent, and 70 percent of the time. Time-shifting was most pronounced for S4, where 73 percent of the time the maximum temperature occurred between 7:00pm and 10:00pm.



* S1 – grass with soil; S2 – grass and various mixed plants with soil; S3 – grass with soil and rock wool; S4 – grass and various mixed plants with soil and rock wool

Figure 3.4: Frequency of Times at Which the Maximum Daily Temperature was Recorded for Control Roof Surface and Various Green Roof Designs

3.3.2 Indoor Room Temperatures

Figure 3.5 shows that on 29 out of 32 observation days, the maximum temperatures in the 9th floor room directly under the green roof were 1˚C to 6˚C lower than the maximum indoor temperatures under the concrete roof (control room). This shows that the high thermal mass of the green roof (compared to the concrete roof) insulates the building, reducing the heat transfer into the building. The green roof also reflects more solar radiation than the concrete roof, reducing the amount of stored heat that can enter the building. On 78 percent of the observation days, the maximum daily temperature in the control room exceeded the ambient maximum daily temperature; whereas on 75 percent of the observation days, the room underneath the green roof was cooler than the ambient maximum daily temperature. There is a stronger correlation between the ambient temperature and the temperature in the control room than with the temperature in the room under the green roofs. On days with higher ambient temperatures, the control room temperature was also elevated. This pattern did not emerge with the room under the green roofs.

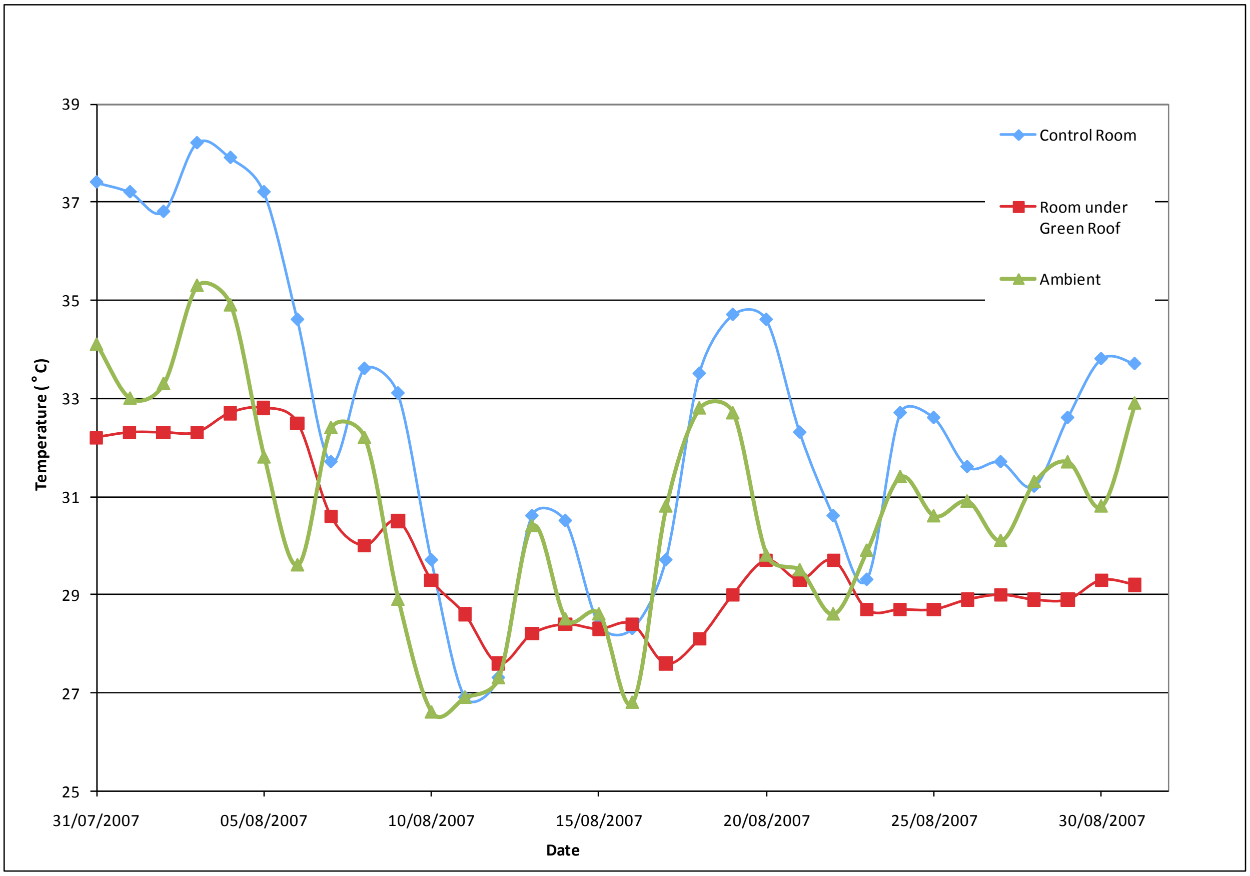


Figure 3.5: Maximum Daily Temperatures of Ninth-Floor Rooms Compared to Ambient Daily Maximum Temperatures (Government of the Hong Kong Special Administrative Region, 2007)

The temperature duration curve in Figure 3.6 shows that the temperature fluctuated more in the control room – between 25˚C and 38˚C – than in the room underneath the green roof, which fluctuated between 26˚C and 32˚C. The more constant and lower temperature in the room underneath the green roof could lead to decreased air conditioning demands compared to the control room.

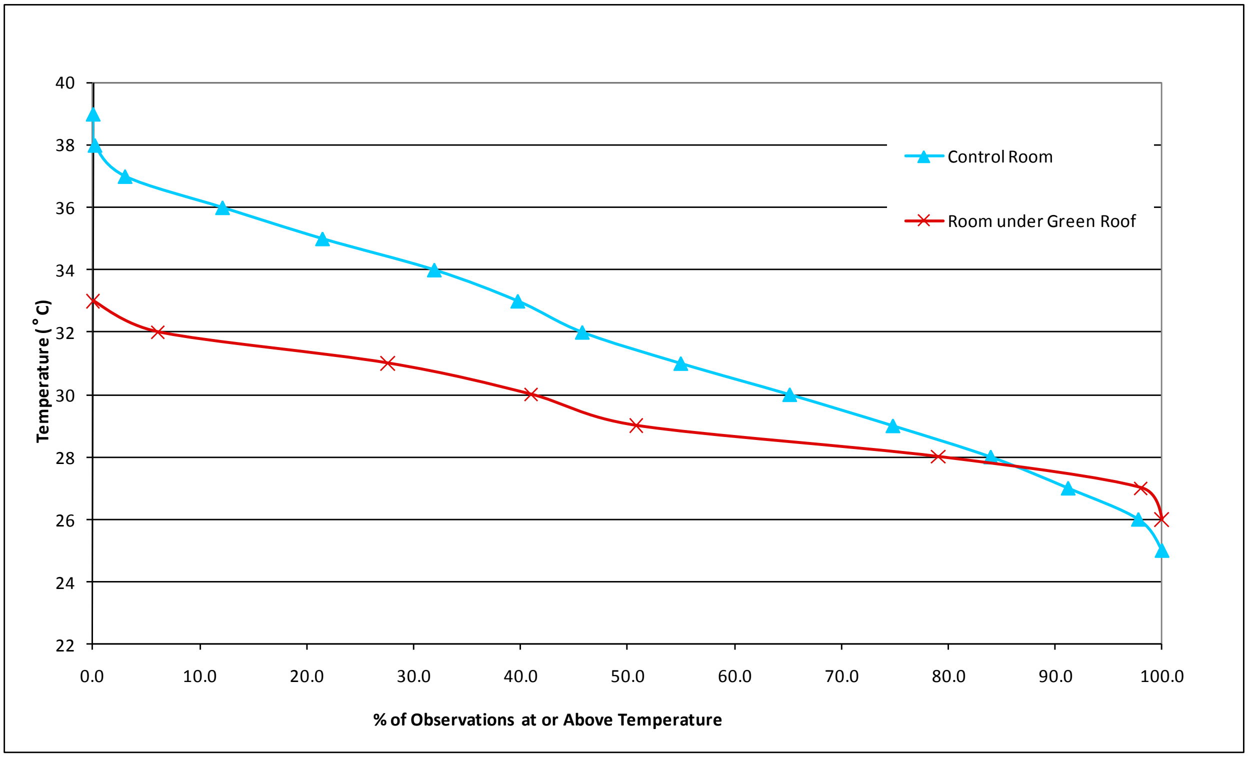


Figure 3.6: Temperature Duration Curve for Ninth-floor Rooms

The results of the Oi Kwan study show that green roofs in Hong Kong have the potential to lower roof surface temperatures compared to a conventional roof, as well as lower indoor air temperature by 1˚C to 6˚C. This can result in tangible cost savings to the building owner. In order to quantify potential energy savings to building owners in Hong Kong, as well as assess other performance measures, a numerical model is beneficial. The Oi Kwan study was limited in that there was a large amount of field data missing; therefore, data collected from another extensive green roof in Hong Kong, the Chuen Seen Mei Chuen (CSMC) green roof, were used for numerical model development and subsequent data analysis, as discussed in Chapter 4.

Chapter 4 – Methodology of CSMC Green Roof Analysis

4.1 Site Description

The Hong Kong Polytechnic University (HKPU) working with the Hong Kong Housing Society (HKHS) installed a 220 m^2 extensive green roof in September 2008 on top of a two-storey building at the CSMC location, in downtown Hong Kong. CSMC is a subsidized housing area in the Kowloon district of Hong Kong. The specific building houses a seniors' home and an education centre. The seniors' home is located on the bottom storey of the building and the after-school education centre is on the top storey of the building. The original roof was a concrete tile roof, as shown in Figure 4.1. Because the building is low-rise, the roof is visible from the surrounding apartment buildings. Installing a green roof provides a good opportunity to improve the aesthetics in the area and increase the green space in addition to reducing the energy consumption of the building.

The green roof consisted of a waterproofing layer, followed by a root protection layer, egg-crate drainage layer, filter fabric layer, substrate layer, and vegetation. The substrate ranged from a depth of 75 to 100 mm and comprised of expanded shale, mushroom compost, and other mineral components. The plants used as vegetation for the extensive green roof were: *Rhoeo discolor*, *Sedum lineare, Arachis duranensis,* and, *Sedum sp*. Overall, the added structural load on the building was 0.75 kPa (Li, Wai, & Lam, 2009). To prevent ponding of water, the green roof was designed with a slightly sloped bottom for collection of rainwater. The rainwater was first collected in a granular stone trench and then diverted towards existing roof drains. More details on green roof construction and plant selection can be found in Li, Wai & Lam (2009). Figure 4.1 shows the building before and after green roof construction.

In November 2008, an automatic watering system with four sprinklers was installed, and watered the green roof twice daily at 8:00am and 8:00pm, for approximately 20 minutes. Issues arose with the watering system related to timer malfunctioning, battery replacement, and lack of water coverage over the roof. Additional sprinklers were installed in April 2009, including a solar powered water timer to prevent battery changes. Issues still existed; therefore, in May 2009 a new water system was installed with six new sprinklers. In total there were 14 sprinklers and two water systems. More details on the irrigation system are discussed in Li, Wai & Lam (2009).

Figure 4.1: Extensive Green Roof on Senior Home and Education Centre in Hong Kong

Temperature, soil moisture, and air quality data (SO_2, CO, NO, NO_2, CO_2) were collected from the green roof over a period of nine months (October 2008 to June 2009). Green roof and indoor temperature sensors collected data at 20 minute intervals throughout the study period. The location of the roof monitoring equipment is shown on Figure 4.2. Soil temperature and moisture were measured at three locations on the green roof. A weather station was also set up on the roof, which collected local weather data at 30 minute intervals. Air samples were collected weekly from the green roof (near the logo), the ground floor entrance to the building, and at street level near the building. A CO_2 sensor was installed on a pole on the roof near the weather station as well as on the first floor of the building to act as a control. Temperature sensors were also placed indoors on both storeys of the building. Four temperature sensors were placed on the ceiling in the seniors' home: in the kitchen, at the entrance, inside a room, and on the ceiling. Two temperature sensors were placed on the ceiling in the education centre on the top floor: one in the hallway and one in the classroom.

One source of error in this thesis results from issues observed during data collection from the CSMC green roof. Over the period of time in which data were collected the following issues were observed (Li, Wai, & Lam, 2009):

- Water timers for green roof irrigation did not always function properly.
- Water sprinklers did not reach all of the areas of the roof.
- Some plants died as the weather became colder and needed to be replaced.
- Mushroom weeds appeared in the *Sedum lineare* region of the green roof which disturbed plant growth. *Sedum lineare* and *Arachis duranensis* needed new seeding due to poor plant growth. By October 2009 good plant growth was observed due to the re-seeding.
- The green roof flooded in August 2009 resulting from filter cloth obstructing the roof drain.

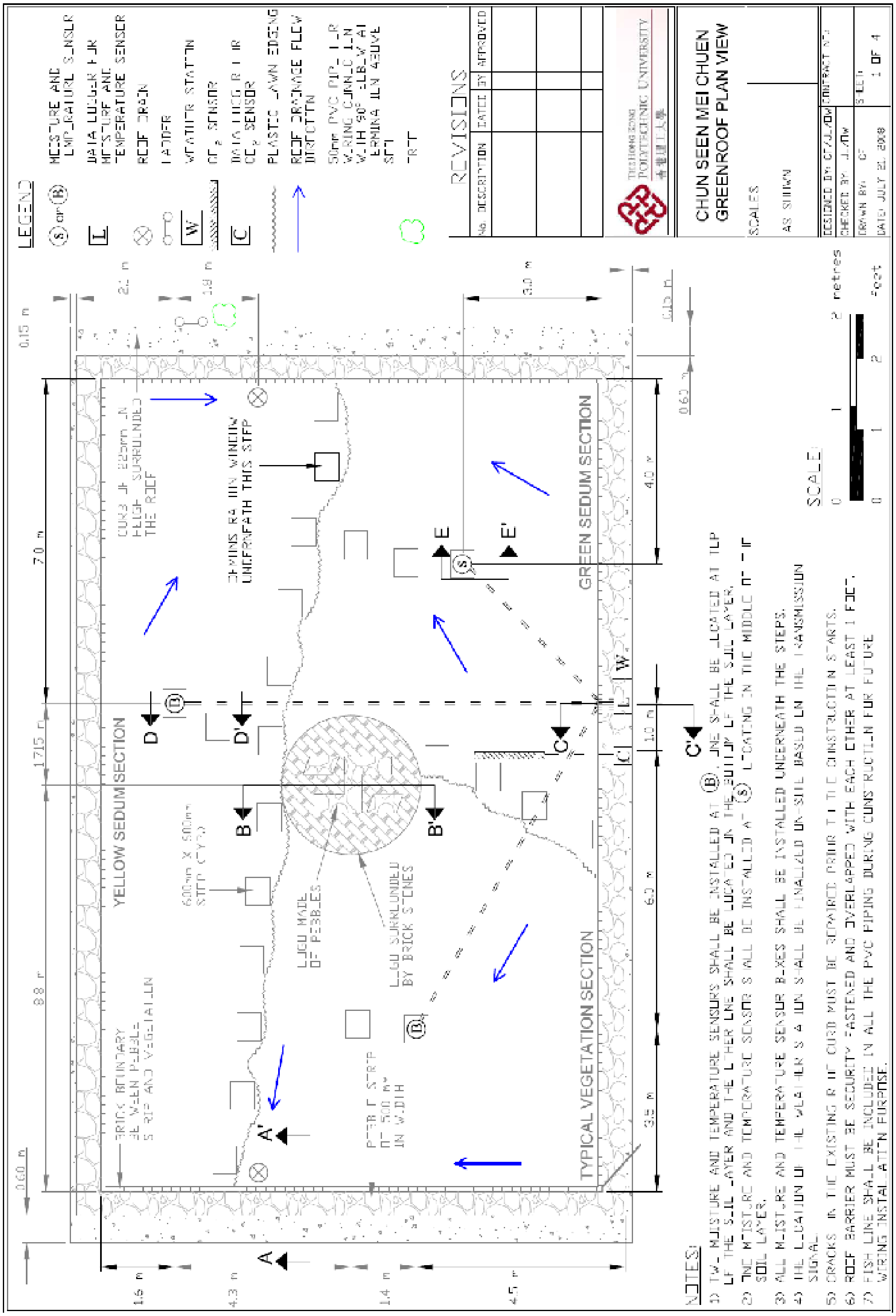


Figure 4.2: Layout of Monitoring Locations (Li, Wai & Lam, 2009)

Since temperature data were not collected from the roof surface and indoor air prior to green roof construction, control roof data cannot be compared to monitored data after green roof construction, as was performed in the case study discussed in Chapter 3. Therefore, the method adopted was to:

- model the building with the green roof in a building energy model;
- compare outputs from the model against monitored data from the green roof in order to calibrate the model;
- use the calibrated model to model the building without the green roof;
- compare the outputs from the green roof model against the original roof model to determine if:
    - there is a reduction in the maximum daily temperature of the green roof compared to the original roof during the data period;
    - there is apparent time shifting of when the maximum temperature of the green roof is reached compared to the original roof; and
    - the temperature of the green roof is more constant than the original roof over the data period through use of the temperature duration curve.

4.2 Building Energy Model Comparison

The building energy model EnergyPlus is selected for the purpose of modelling the CSMC building after careful review of other comparable building energy models. The building energy models reviewed are BLAST, DOE-2, ECOTECT, and EnergyPlus.

The Building Loads Analysis and System Thermodynamics (BLAST) tool was developed in the late 1970s and early 1980s as a joint project between the Army Construction Engineering Research Laboratory and the University of Illinois. There are three subprograms in BLAST: Space Loads Prediction, Air System Simulation, and Central Plant. Space Loads Prediction uses weather data to simulate the hourly space load in the building and perform a heat balance on the air in the rooms. Air System Simulation calculates the steam, gas, hot water, chilled water, and electric demands of the air handling system and building. Central Plant then simulates the building's fuel consumption (Crawley, Hand, Kummert, & Griffith, 2005). BLAST has mainly been used to size heating, ventilation, and air conditioning (HVAC) equipment (Sailor, 2008). The most recent version of BLAST was released in 1998 and it is no longer being updated (Crawley et al., 2005).

DOE-2 was developed around the same time as BLAST by the Department of Energy (DOE). DOE-2 is considered the industry standard for building energy modelling. Using hourly weather data DOE-2 can determine the hourly energy usage of a building as well as the cost. The model can also be used to help improve energy efficiency by varying building parameters. There are four subprograms for simulation: LOADS, SYSTEMS, PLANT, and ECONOMICS. The output from one subprogram is the input into the next subprogram, in a sequential fashion. The LOADS subprogram calculates for each temperature the hourly heating/cooling load. The SYSTEMS subprogram calculates the performance of secondary systems such as fans, ducts and coils. The PLANT subprogram calculates the performance of primary systems such as chillers, boilers, storage tanks, and cooling towers. The ECONOMICS subprogram then calculates the energy costs. Both DOE-2 and BLAST are good programs for analyzing the energy performance of new and retrofit buildings. (Crawley et al., 2005)

ECOTECT was developed by architects and is mainly used by architects, but is gaining popularity among engineers and environmental building designers. Unlike BLAST, DOE-2, and EnergyPlus, ECOTECT is a visual and interactive 3D modelling software tool that has many performance analysis functions (Crawley et al., 2005). Autodesk has recently acquired ECOTECT. The purpose of ECOTECT is to look at the overall building design process in order to create an energy efficient building instead of designing individual parts such as the HVAC system to meet the needs of the building design. Some of the applicable features of ECOTECT are calculation of: internal building temperatures, heat and cooling loads, multi-layer material insulation (used in conjunction with other codes such as EnergyPlus), solar radiation on windows and building surfaces (Autodesk, 2008). Although ECOTECT can perform internal calculations, more technical calculations need to be performed by importing and exporting to other programs such as EnergyPlus, Radiance, NIST FDS etc (Crawley et al., 2005).

EnergyPlus, released by the DOE in 2001, combines the best features of BLAST and DOE-2. EnergyPlus is a simulation program and does not have a user interface. It is often combined with a third party interface such as DesignBuilder, but can also be used as a standalone program. Some of the main features of EnergyPlus are: integrated and simultaneous solutions, sub-hourly user defined time steps, transient heat conduction, solution based on heat balance, ground heat transfer modelling, heat and mass transfer model combined, text based weather files, thermal comfort models, advanced fenestration models, daylight controls (e.g., glare simulation), and atmospheric pollution (United States (U.S.) DOE, 2009). One of the main reasons to replace BLAST and DOE-2 is that these models were written in older versions of FORTRAN code, which are becoming obsolete.

Similar to BLAST and DOE-2, and unlike ECOTECT, one of the main benefits of EnergyPlus is that is an open source code. The code is available to anyone and can be revised by the public, subject to proper testing and verification. Another benefit of EnergyPlus is that it is built as a modular system, which gives developers and researchers the capability to develop systems independently with minimal interference with other modules. Additionally, in-depth knowledge of the entire program is not necessarily required or necessary (U.S. DOE, 2009).

The two main modules of EnergyPlus are the heat and mass balance simulation and the building system simulation. Recently, Sailor (2008) developed a green roof module "eco roof" that has been tested, using data from a field study conducted in Florida, and integrated into EnergyPlus. One of the limitations of the original green roof model in EnergyPlus was that it could only be applied to one green roof at a time (Sailor, 2008). The most recent release of EnergyPlus, released in October 2010, allows for modelling of multiple green roofs. In addition to all of the reasons described above, the DOE has committed to current and future development of EnergyPlus, making it a smart selection for use in this thesis.

4.3 EnergyPlus Input Simulation Parameters

Using EnergyPlus Version 5.0, the two-storey CSMC building in Hong Kong was modelled before and after green roof installation. Table 4.1 outlines the categories of information needed to model the building (U.S. DOE, 2010). The main input parameters needed to model the CSMC building are: building dimensions, construction material, roof vegetation, window air conditioner specifications, and weather details for Hong Kong.

When modelling the CSMC building in EnergyPlus simplifying assumptions were made. The building was modelled as a simplified two-zone building, meaning that each storey was modelled as an individual zone – one open room, instead of partitioned into smaller rooms and stairwells. This assumption allowed the output from the model to be analyzed in a less complicated and more practical manner. The top floor was of more interest in the model than the bottom floor as temperature and energy reduction resulting from green roof installation is more prominent on the storey directly beneath the green roof. The detailed input parameters are included in Appendix A. Although the CSMC building was simplified for modelling purposes, all input parameters were justified through literature values or from assumptions made by the EnergyPlus software.

Table 4.1: Summary of Input Parameters Required for Modelling Building

Input	Description
Version	Version of EnergyPlus used in the simulation (5.0)
SimulationControl	Specifies what types of simulation calculations will be performed.
Building	Describes parameters such as coordinate system, terrain, solar distribution, etc.
ShadowCalculation	Determines the sun's position for design days.
SurfaceConvectionAlgorithm :Inside	The 'detailed' natural convection model relates heat transfer coefficient and temperature difference. This is the default selection.

Input	Description
SurfaceConvectionAlgorithm:Outside	Selects exterior convection model to be used. Choice of 6. DOE-2 selected.
HeatBalanceAlgorithm	Selects the type of moisture and heat transfer algorithm to be used for calculations. ConductionTransferFunction is the default choice and does not include moisture in construction materials.
Timestep	The time interval used for calculating heat transfer and loads. The number must be divisible into 60.
Site:Location	Outlines the specifics for the location of the building.
SizingPeriod:DesignDay	Specifies the input parameters for a “design day” simulation which is then used for load calculations.
RunPeriod	Specifies over which months the simulation will run.
Site:GroundTemperature:BuildingSurface	Sets the ground temperature of the outside building surface for each month.
RoofIrrigation	Defines the amount of irrigation on the surface of the green roof, according to a schedule. SmartSchedule only irrigates if soil moisture is greater than 30 percent.
ScheduleTypeLimits	Sets the limits for the values in schedule types.
Schedule:Compact	Accesses all features of the schedule components at the same time.
Material	Defines the thickness, conductivity, density and specific heat of the construction materials.
WindowMaterial:Glazing	Defines the thickness, solar transmittance and reflectance of window material.
WindowMaterial:Gas	Defines the gas material properties (i.e., air) used in windows.
Material:RoofVegetation	Defines the properties of the green roof layer such as height of plants, leaf area index, leaf reflectivity, and soil properties.
Construction	Defines each construction layer from outside to inside.
GlobalGeometryRules	Specifies the rules for defining geometric parameters and where surface vertices begin (e.g., upper left corner).
Zone	Defines the zone origin (x,y,z), direction relative to north and other elements to set up the zone.
BuildingSurface:Detailed	Describes each of the surfaces and details the coordinates of each vertex in order to build a surface.
FenestrationSurface:Detailed	Defines the coordinates for subsurfaces such as windows and doors.
People	Defines the number of people in each zone in order to determine effect of each occupant on the space conditions.
Lights	Defines the properties for lights.
Sizing:Zone	Data used to calculate zone design air flow for a single zone. Zone inlet supply air temperature and humidity are needed.
ZoneControl:Thermostat	Controls a zone to a specified temperature.
ThermostatSetpoint:DualSetpoint	Used for thermostats where both heating and cooling setpoints are set through a schedule.
ZoneHVAC:WindowAirConditioner	Specifies the parameters of the window air conditioner such as outdoor air mixer, fan, direct expansion cooling coil.
ZoneHVAC:EquipmentList	Lists all HVAC equipment for each zone.
ZoneHVAC:EquipmentConnections	Defines remaining HVAC details for each thermal zone.
Fan:ConstantVolume	Defines the parameters for a constant air volume fan operating continuously based on a timed schedule.
Coil:Cooling:DX:SingleSpeed	Defines the inputs for the single speed DX water coil to determine the coil performance. The model requires 5 curves (e.g., biquadratic, quadratic, etc).

Input	Description
NodeList	Identifies all nodes.
OutdoorAir:NodeList	Specifies the name of the HVAC system node.
Curve:Quadratic	Needed to characterize HVAC equipment performance.
Curve:Biquadratic	Needed to characterize HVAC equipment performance.
Output:VariableDictionary	Contains the key variable names for each simulation.
Output:Surfaces:List	Used for reviewing the accuracy of surface geometry inputs.
Output:Surfaces:Drawing	Produces a DXF file of the surfaces.
Output:Constructions	Reports the calculated results related to conduction transfer functions for each construction.
Output:Table: SummaryReports	Specifies the predefined outputs that will be reported.
OutputControl:TableStyle	Specifies the output table style.
Output:Variable	Reports time series data for specified parameters at various frequencies.
Output:Meter	Allows easy graphing and comparison with "normal" values (such as Zone Temperature or Outdoor Temperature).

The CSMC roof – prior to addition of the green roof – was modelled as a concrete roof structure. Table 4.2 outlines the main properties of the concrete roof. The parameters for concrete were taken from the EnergyPlus data library (M08 200mm lightweight concrete block (filled)).

Table 4.2: Input Parameters for Original Roof

Parameter	Concrete Slab
Thickness	203.2 cm
Conductivity (U value)	0.26 W/m-K
Density	464 kg/m^3
Specific heat	880 J/kg-K

Although a variety of plants – *Rhoeo discolor*, *Sedum lineare, Arachis duranensis,* and *Sedum sp.* – were used for the green roof, for model simplification, the specific parameters used in the EnergyPlus model were based on the properties of sedum, shown in Table 4.3. The actual soil consisted of expanded shale, mushroom compost, and mineral components, but was modelled in EnergyPlus based on the properties for sandy loam soil, shown in Table 4.3. From the perspective of heat transfer, the most important properties of the vegetation layer are the height of plants, leaf area index (LAI), albedo, and stomatal resistance. The LAI represents the ratio between the leaf surface area and the soil surface area – with values typically ranging from 0.5 to five, where the higher the LAI the lower the energy consumption in the summer (Sailor, 2008). The albedo represents the ability of the plant surfaces to reflect solar radiation, and the stomatal resistance represents the rate at which the leaf's stomata can transpire moisture. The most important properties of the soil layer are its specific heat capacity, density, and thermal conductivity.

The green roof model specified roof irrigation daily at 8:00am and 8:00pm for approximately one hour. Sailor (2008) used 1 cm/week for green roof irrigation for a soil thickness of 0.1 m. Based on Sailor, 0.7 mm per watering period was used as an input to the irrigation schedule for the CSMC green roof model in EnergyPlus. A "smart schedule" was used which only irrigates the green roof if soil moisture is below 30 percent. The moisture level in the soil is automatically calculated by the EnergyPlus model.

Table 4.3: Input Parameters for Green Roof Vegetation and Soil

Parameter	Value	Source
Height of plants	0.2 m	Green roof construction specifications
LAI (leaf area index)	4.6	Feng, 2010
Leaf reflectivity (albedo)	0.2	Gaffin, 2009
Leaf emissivity	0.95	default assumption
Minimum Stomatal Resistance	180 s/m (default assumption)	default assumption
Soil Thickness	0.08 m	Green roof construction specifications
Conductivity of Dry Soil	0.4 W/m-K	Abu-Hamdeh, 2001
Density of Dry Soil	766 kg/m^3	Lazzarin et al., 2005
Specific Heat Capacity of Dry Soil	1000 J/kg-K	Lazzarin et al., 2005

For the top floor of the building, a window air conditioning unit was simulated using a schedule in EnergyPlus on weekdays from 8:00am until 7:00pm, from the beginning of April until the end of September. The main input components for a window air conditioner are the maximum supply air flow rate, the maximum outdoor air flow rate, and the availability schedule. Associated with each window air conditioner, EnergyPlus requires specifications for an outdoor air mixer, a fan, and a direct expansion cooling coil (U.S. DOE, 2010). Details for all of these components are specified in Appendix A.

EnergyPlus has compiled weather data for Hong Kong over selected years during 1982 to 2003, which is available for download in EnergyPlus weather format[2]. The weather file includes information such as temperature, dew point, relative humidity, wind speed, and wind direction. This file was modified to use the climate data

[2] http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=CHN/cname=China

(temperature, dew point, and relative humidity) collected from the on-site meteorological station. The modified file was used in the EnergyPlus simulations for model calibration.

4.4 Sensitivity Analysis

In order to test model performance, a sensitivity analysis was conducted on key parameters. Key parameters tested were related to green roof specifications, building construction material, and the HVAC system. Specifically the effect of varying soil thickness and LAI for the green roof, conductivity of the concrete material, and fan flow rate in the HVAC system were tested for model stability.

Table 4.4 presents the values used for each sensitivity analysis simulation. The sensitivity analysis was performed using the “Parametric:SetValueForRun” function in EnergyPlus. This function allows the user to run the model multiple times by changing the value of one parameter. The energy consumption output from the model – from the months April through September – was then analyzed to determine if the energy consumption was affected by the changing values for each parameter. The bold values in Table 4.4 represent the baseline values used in the model. Figure 4.3 to Figure 4.5 show the results of the sensitivity analyses based on the difference in energy consumption between the baseline value and the adjusted values.

The results of the sensitivity analysis show that as soil thickness and LAI for the green roof increase, energy consumption decreases, consistent with results identified by Palomo Del Barrio (1997). As shown on Figure 4.3 to Figure 4.5, the relationship between energy consumption and LAI is more linear than the relationship between energy consumption and soil thickness. For the regular concrete roof, as conductivity increases the energy consumption increases as well; however the energy difference between 0.16 W/m-K and the baseline conductivity (0.26 W/m-K) is greater than the energy difference between 0.36 W/m-K and the baseline conductivity. The fan flow rate does not affect the energy consumption of the building; as such the value selected for the flow rate is not critical.

Table 4.4: Parameters and Values Tested for Sensitivity Analysis

Soil Thickness (m)	**LAI**	**Density (kg/m^3)**	**Fan Flow Rate (m^3/s)**
0.06	1	0.06	0.1
0.08	2	0.16	**0.6**
0.1	3	**0.26**	1.1
0.15	4	0.36	1.6
0.2	**4.6**	0.46	
	5		

^ Bold value represent the baseline values used in the model

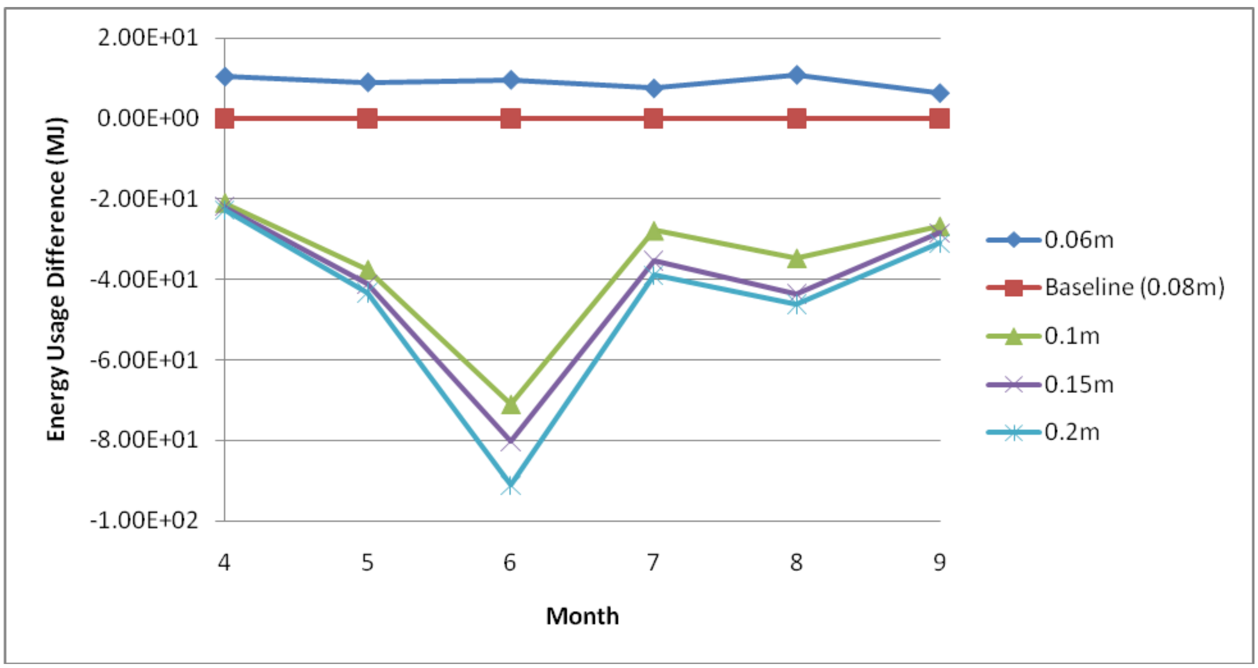


Figure 4.3: Soil Thickness Sensitivity Analysis for the Green Roof

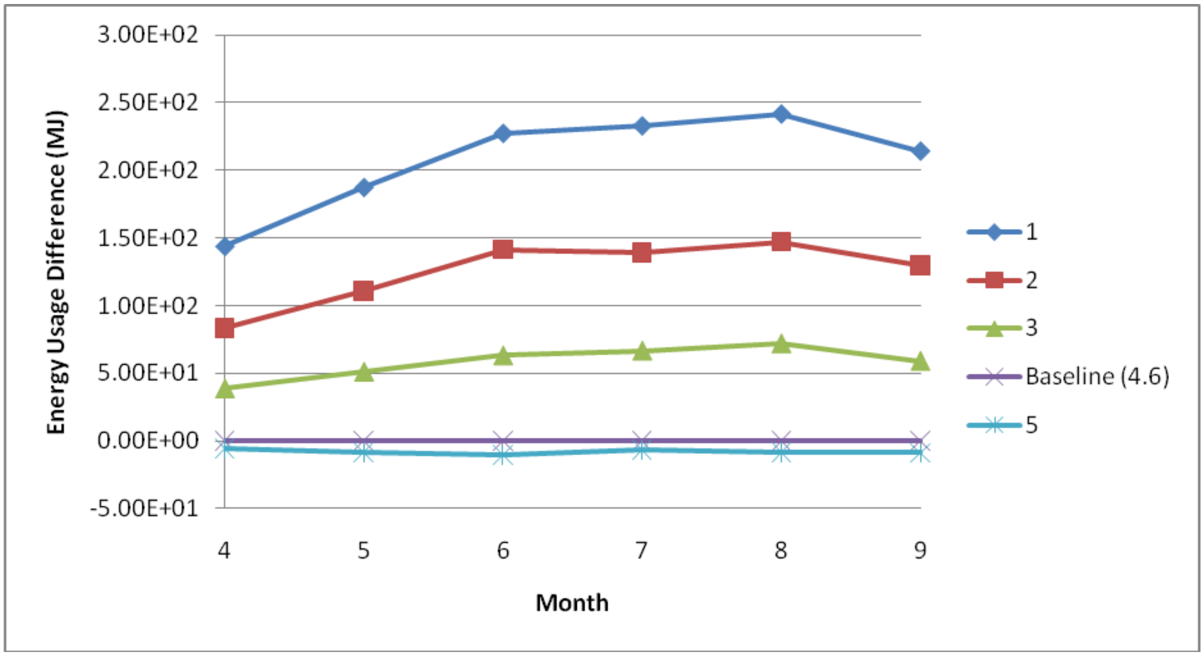


Figure 4.4: Leaf Area Index Sensitivity Analysis for the Green Roof

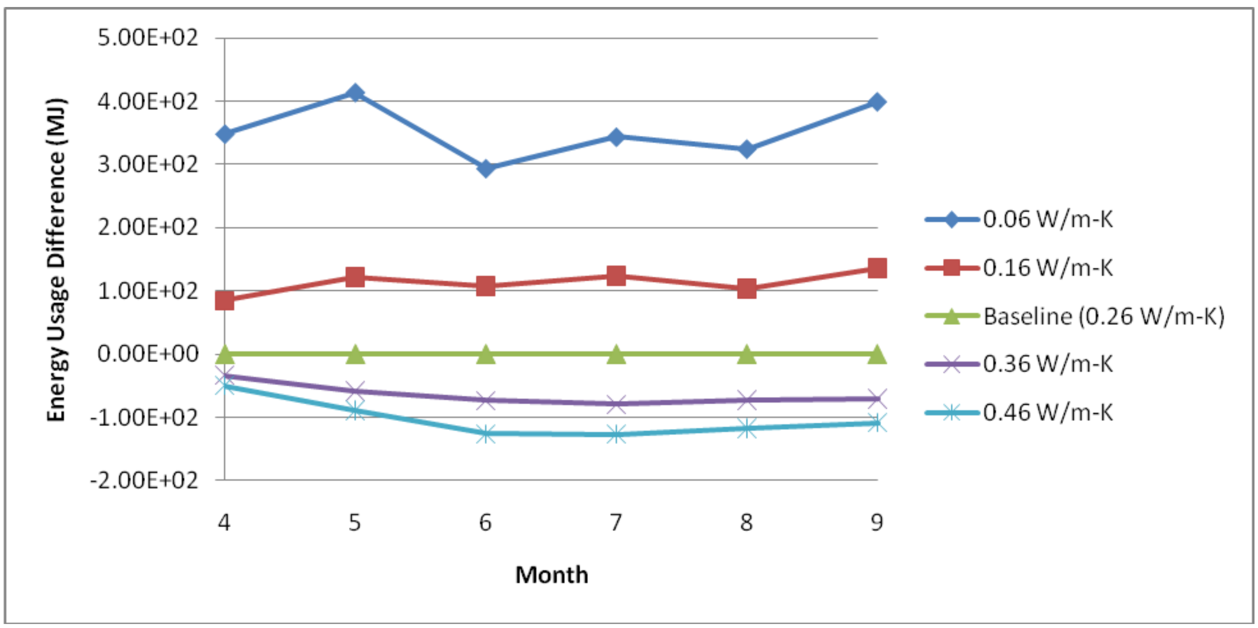


Figure 4.5: Concrete Conductivity Sensitivity Analysis

4.5 Model Calibration

The calibration process was executed by first identifying the input parameters in EnergyPlus that have a strong influence on temperature and energy usage. Sun & Reddy (2006) discuss some of the common sensitive parameters in building energy simulation programs. After strongly influential parameters were identified (Table 4.5), these values were adjusted through a trial and error approach in order to obtain a model that matched existing monitoring data.

Table 4.5: Input Parameters Modified for Model Calibration

Parameter	Final Value	Units
Material Conductivity	0.26	W/m-K
Material Density	464	kg/m^3
Window Air Conditioner Max Supply Air Flow Rate	0.6	m^3/s
Fan Efficiency	0.9	-

The model was calibrated using the green roof surface temperature as well as indoor temperature data collected over February and June 2009, after green roof installation, from the top floor of the building. Calibration was limited as green roof surface temperature data only exist for the month of June. As such predicted rooftop data from the green roof model in EnergyPlus can only be compared to one month of monitoring data.

Roof surface and indoor temperature data do not exist prior to green roof installation; therefore, the model was calibrated by comparing the temperature data predicted by the model with the green roof against monitored data collected from the green roof. The objective is for the predicted indoor air temperatures from the model to match the field data collected to a certain degree of error – the root mean square (RMS) error of the data points should be less than or equal to ± 20 percent, consistent with the RMS error used by Sailor (2008). The fractional error between the data points was first calculated, followed by the percent RMS error according to the following equations:

$$T_{Error} = \frac{T_{modelled} - T_{monitored}}{T_{monitored}}$$

where,

T_{Error} = fractional difference between the modelled and monitored temperatures

$T_{modelled}$ = the predicted indoor temperature from the EnergyPlus model (ºC)

$T_{monitored}$ = the indoor temperature collected from monitoring data (ºC)

$$\% RMS = \sqrt{\frac{T_{Error(i)}{}^2 + T_{Error(j)}{}^2 + \cdots + T_{Error(n)}{}^2}{n}} \times 100$$

The results of the calibration are presented in Section 5.1. Once the models are calibrated they can be used to analyze a wide range of situations without having to collect field data over an extended period of time.

4.6 Scenario Analysis

The calibrated models described in Section 4.5 were used for analysis of certain scenarios. Although a meteorological station was set up on the edge of the roof of the CSMC building, EnergyPlus does not recommend using data from a one year period in the EnergyPlus simulation model (Crawley, 1998). Data from one year cannot represent long term weather patterns, whereas data over many years will predict energy consumption that is more representative of the site over the long-term. Therefore, once the model was calibrated, the Hong Kong weather file from EnergyPlus was used for the scenario analysis. The climate data in the EnergyPlus weather file were obtained from a meteorological station at 22.32 N, 114.17 E, which is in the same vicinity as the CSMC building.

The green roof model was used to predict the energy savings of the building by using a green roof during the months where air conditioning is used (April through September). This was compared to the predicted energy consumption from the model without the green roof over the same time frame. The reduction in energy usage in the building was translated into tangible cost savings, by using the cost outlined by the Hong Kong Electric Company of 124.1 HKcents per kWh or CAD$0.15/kWh (HK Electric, 2011).

Using a green roof may not be the best method to reduce the energy consumption of the CSMC building. Therefore, the building model was used to compare the temperature differences, predicted energy consumption and associated operational cost of a green roof against other alternatives such as:

- cool roof (reflective roof);
- insulation layer; and
- reflective windows.

The effect of irrigation on green roof performance was also studied by running a simulation with different irrigation schedules and quantities of water per irrigation cycle.

4.6.1 Cool Roof

Many standard dark roofs use materials that absorb solar radiation; however, materials that reflect solar radiation reduce the amount of heat that enters a building. Reflective roofing materials are also referred to as cool roofs. Jo et al. (2010) conducted an experiment on a commercial building in Arizona comparing a cool roof to a typical roof and found approximately 1.5 percent cost reduction in monthly electricity usage by covering 50 percent of the surface with a cool roof coating. The cool roof surface used in that experiment was white 3/8" (0.95 cm) marble roofing aggregate with specifications from the Cool Roof Rating Council (CRRC). The CRRC (n.d.), a product rating system in the United States, has developed standard methods to rate the radiative properties – solar reflectance and thermal emittance – of materials used for cool roofs.

The cool roof specifications used in Jo et al. (2010) were used as inputs to the CSMC EnergyPlus model (Table 4.6) to determine if a cool roof would provide greater energy and cost savings than the green roof. Low thermal and solar absorptance are important characteristics for cool roofs. A roof that reflects most of the solar radiation will transfer less heat into the building. Furthermore, roofs with low thermal absorptance will reach thermal equilibrium at a lower surface temperature than a roof with high thermal absorptance. Once thermal equilibrium is reached the surface temperature of the roof stops increasing. The R-value of building insulation is a measure of the ability of a material to stop heat flow (U.S. EPA, 2008). The cool roof properties were entered in the Material:NoMass class in EnergyPlus.

Table 4.6: Input Parameters for Cool Roof

Parameter	Marble Aggregate
Thermal Resistance (R-value)	4.75 m^2-K/W
Thermal Absorptance	0.15
Solar Absorptance	0.29

4.6.2 Insulation Layer

Adding additional insulation to a roof is another method to reduce surface temperature and energy consumption. Cool roofs reflect solar radiation; however, they do not prevent thermal heat loss from buildings. Bianchi et al. (2007) concluded that similar energy requirements are needed for a cool roof as by adding minimal insulation to a typical dark roof membrane. Adding an insulation layer to a typical dark roof can reduce heat loss, especially during the cooler months. Considering the mild winter climate in Hong Kong, this is not a concern; however, adding an insulation layer can also reduce thermal heat gain into the building during the summer months.

Insulation is described mainly in terms of its R-value, the ability of a material to resist heat flow. The higher the R-value, the greater the material resists heat flow. Polyisocyanurate (polyiso) insulation typically has an R-value from R-5.6 to R-8 (or R-0.98 to R-1.4 in metric units) per inch of insulation (U.S. DOE, 2011a) – one of the highest R-values compared to other types of insulation. It contains a low conductivity gas that is non-ozone depleting and has low global warming potential – until recently the polyiso industry was using hydrochloroflourocarbons. The insulation layer was added in EnergyPlus using the Material:NoMass class, since polyiso is described mainly in terms of its R-value (see Table 4.7). In the EnergyPlus simulation, the insulation was installed below the roof membrane.

Table 4.7: Input Parameters for Added Roof Insulation

Parameter	Polyiso Roof Insulation
R-value	1.4 m^2-K/W

4.6.3 Reflective Windows

Reflective films can be added onto windows to reduce the heat transmitted into buildings during the summer months. Reflective windows block solar radiation during the winter months (U.S. DOE, 2011b); however, since the weather in Hong Kong is typically mild during the winter, this is not a significant concern.

A pyrolytic titanium coating for windows – selected from the EnergyPlus library – was used to model the CSMC building to determine if greater energy savings are obtained by using reflective windows or a green roof. The window specifications are shown in Table 4.8 and entered in the WindowMaterial:Glazing class in EnergyPlus.

Table 4.8: Input Parameters for Reflective Window

Parameter	Pyrolytic Titanium Window
Thickness	0.003 m
Solar Transmittance at Normal Incidence	0.74
Front Side Solar Reflectance at Normal Incidence	0.09
Back Side Solar Reflectance at Normal Incidence	0.1
Visible Transmittance at Normal Incidence	0.82
Front Side Visible Reflectance at Normal Incidence	0.11
Back Side Visible Reflectance at Normal Incidence	0.12
Infrared Transmittance at Normal Incidence	0
Front Side Infrared Hemispherical Emissivity	0.84
Back Side Infrared Hemispherical Emissivity	0.2
Conductivity	0.9 W/m-K

Chapter 5 – Results and Discussion

5.1 Model Calibration Results

Air conditioning was specified in the model from April to September; therefore, calibration was performed during a summer month (June) when air conditioning was used and during a winter month (February) when air conditioning was not used. The adequacy of the model is discussed in terms of both roof surface temperature and indoor air temperature.

5.1.1 Summer Month

The green roof model was calibrated over June 2009. The green roof model was compared to monitoring data collected in June 2009 from the green roof surface and the rooms below the green roof. Indoor air monitoring data were collected from a classroom and the hallway in the CSMC building, averaged together and compared against data predicted from the EnergyPlus green roof model. Figure 5.1 presents both monitored and predicted green roof surface temperature data together over the month of June. Figure 5.2 presents both monitored and predicted indoor air temperature data over the month of June for the area directly below the green roof.

The predicted temperature data from EnergyPlus follow the same pattern as the monitored data. Occasionally, the green roof model over-predicted the roof surface temperature data and other times under-predicted the roof surface temperature data. For the indoor air temperature data, the monitored data are consistently higher than the predicted data. This pattern follows throughout the month of June.

Both figures present ambient air temperature as measured from the weather station on the CSMC roof. The predicted and monitored temperature data both generally peak after the ambient air temperature peaks, as shown on Figure 5.1 and Figure 5.2. There are exceptions, such as June 26th and 27th where the predicted indoor air temperature fluctuates throughout the day, but the monitored indoor temperature is fairly constant. The ambient air temperature shows fluctuations on those days although much lower than the predicted indoor air temperature. This pattern could point to issues in the monitoring data collected on those days.

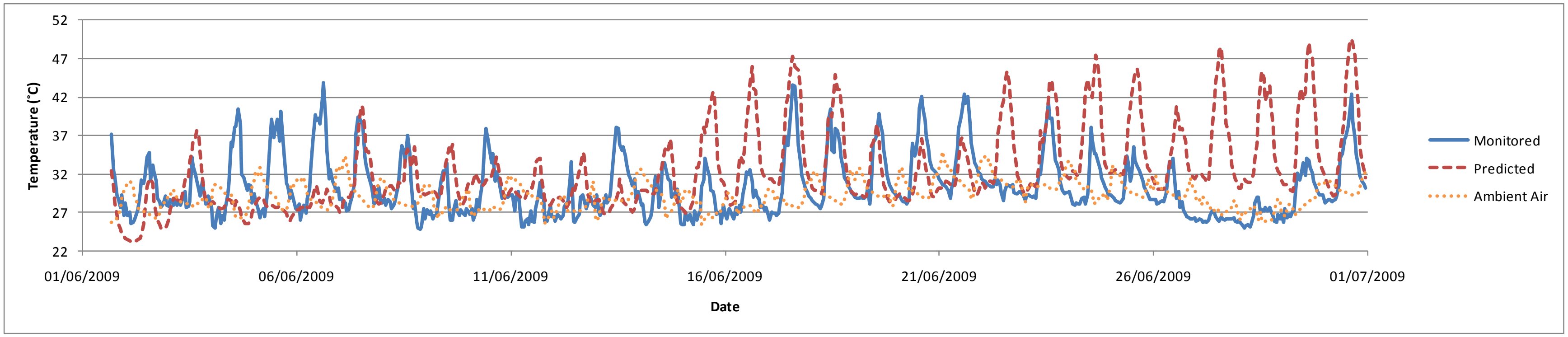


Figure 5.1: Monitored and Predicted Green Roof Surface Temperature Data (June 2009)

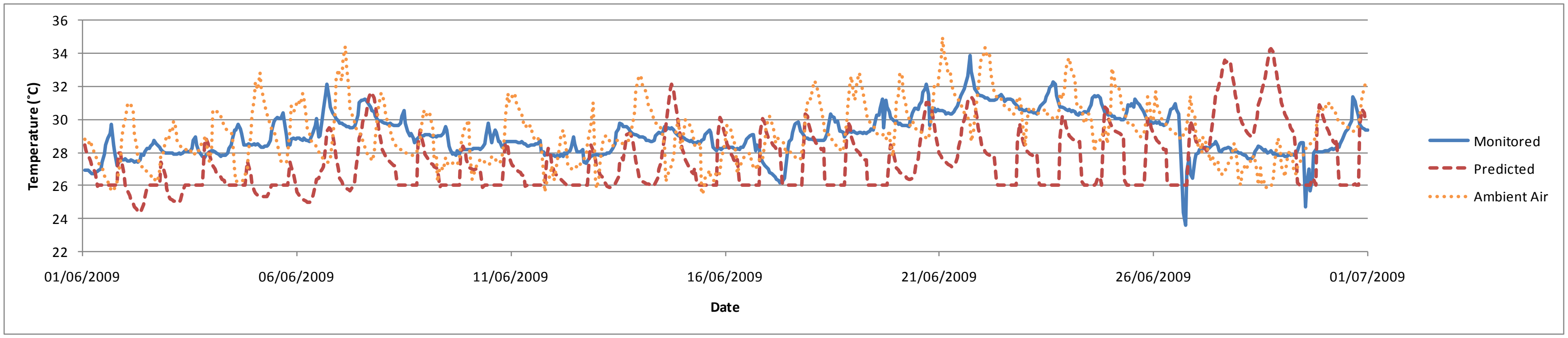


Figure 5.2: Monitored and Predicted Indoor Air Temperature Data below the Green Roof (June 2009)

The relationship between predicted and monitored green roof surface temperature data is shown in Figure 5.3. Similarly, the relationship between predicted and monitored indoor air temperature data is shown in Figure 5.4. The linear line shows the ideal scenario, if the predicted and monitored data were the same. The dots represent all of the temperature data from the month of June. The closer the dots are to the linear line, the more similar the predicted and monitored data. There are times throughout the month of June where the predicted and monitored data closely align and other times where they are farther apart. Overall, the results of the calibration show that the total RMS error of the roof surface temperature and the indoor air temperature for the month of June were ± 16 percent and ± 10 percent, respectively. The RMS error was calculated according to the method described in Section 4.5. The results fit within the acceptable margin of error of ± 20 percent stated in Section 4.5.

To illustrate the typical daily temperature trend, Figure 5.5 and Figure 5.6 present the surface and indoor air temperature trend over one day, June 21st (when air conditioning was not used). The roof and indoor air temperature are lowest in the early morning, approximately at 6:00am. As the day progresses the temperature slowly increases. The roof surface temperature peaks at approximately 12:00pm to 1:00pm and the indoor air temperature peaks at approximately 5:00pm. The roof surface and indoor air temperature slowly decrease throughout the night. At approximately 12:00pm, the maximum monitored roof surface temperature is 39.3˚C and the maximum predicted roof surface temperature is 36.4˚C. At approximately 5:00pm, the maximum monitored indoor temperature is 33.9˚C and the maximum predicted indoor temperature is 31.3˚C.

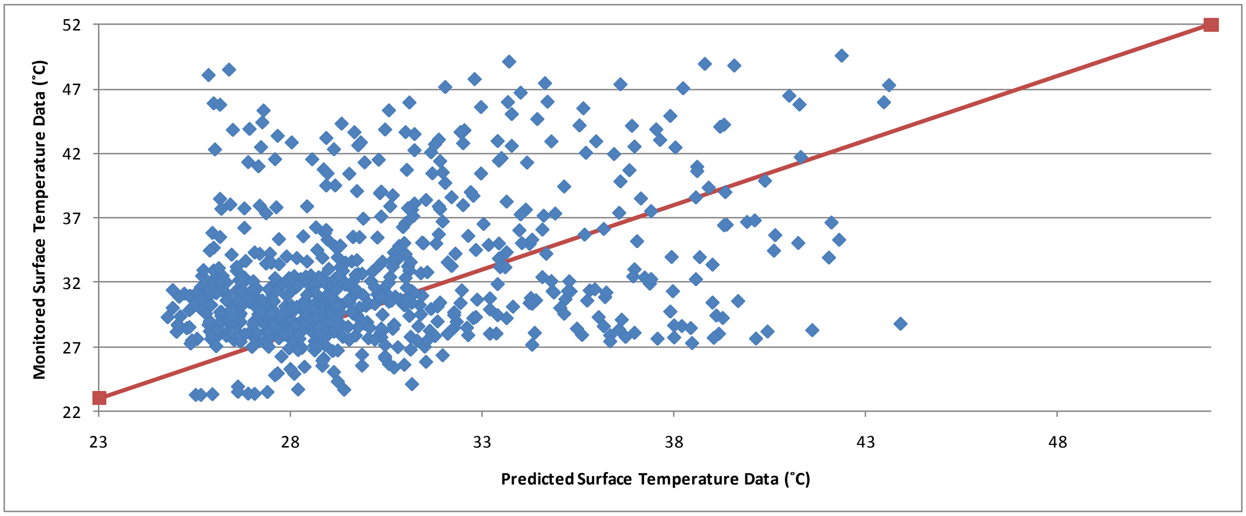


Figure 5.3: Correlation between Predicted and Modelled Green Roof Surface Temperature Data (June 2009)

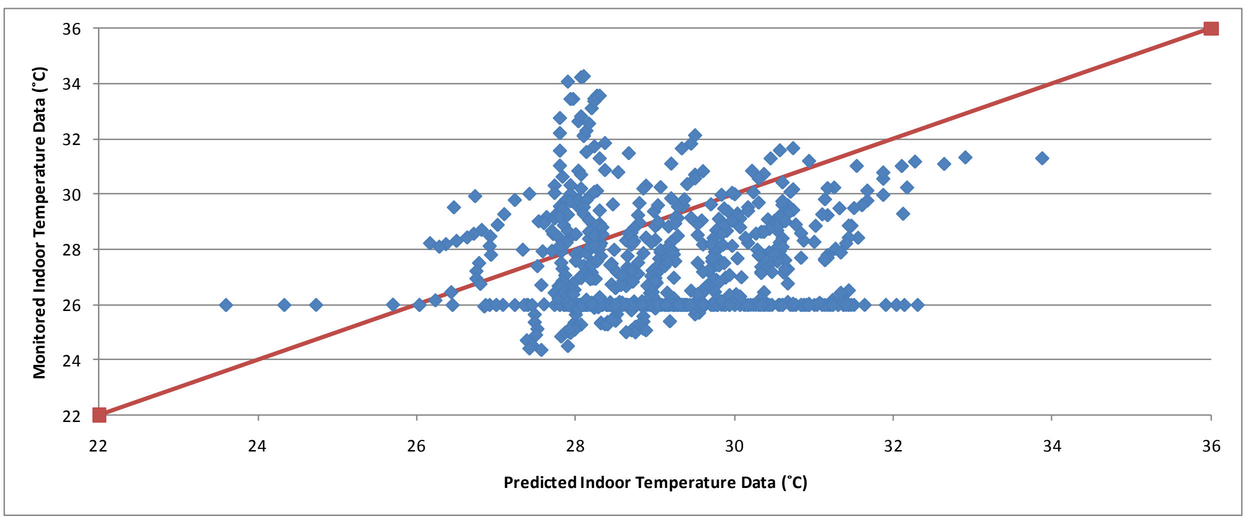


Figure 5.4: Correlation between Predicted and Modelled Indoor Air Temperature Data below the Green Roof (June 2009)

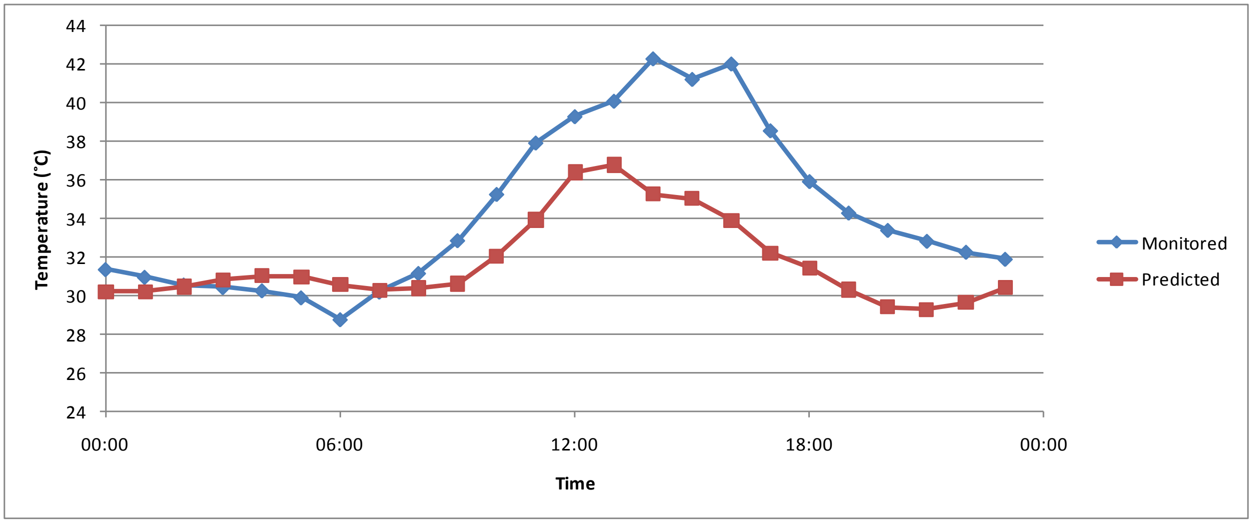


Figure 5.5: Monitored and Predicted Green Roof Surface Temperature over One Day (June 21, 2009)

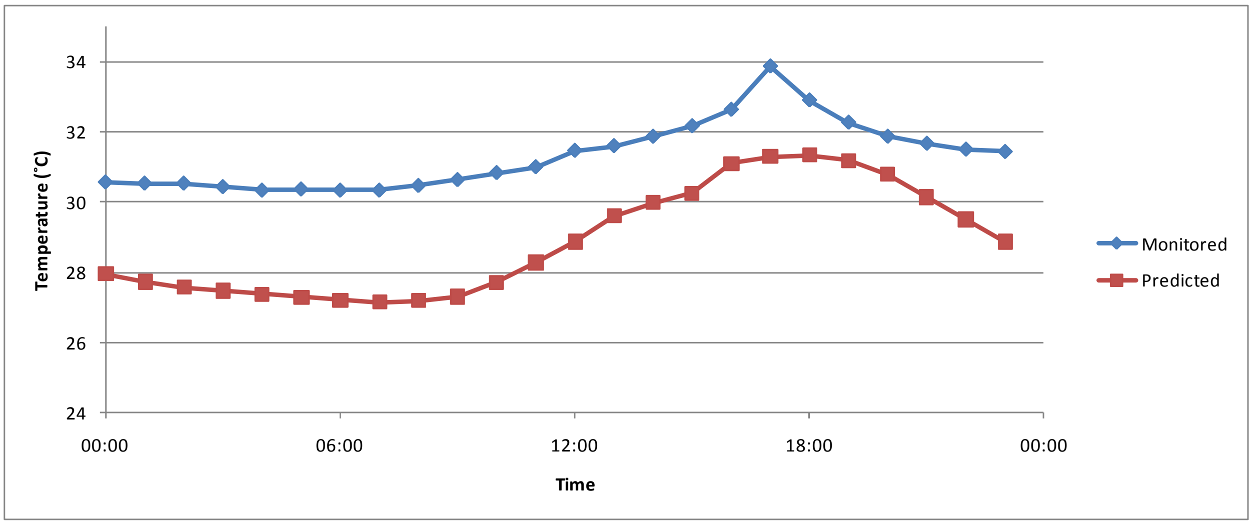


Figure 5.6: Monitored and Predicted Indoor Air Temperature below the Green Roof over One Day (June 21, 2009)

5.1.2 Winter Month

The green roof model was also compared to monitoring data during February 2009, a winter month where air conditioning was not used. The purpose was to determine the adequacy of the green roof model under simplified conditions. Roof surface temperature data were not available; therefore only the indoor air temperature data were used for this scenario. Indoor monitoring data were collected from a classroom and the hallway in the CSMC building, averaged together and compared against data predicted from the EnergyPlus green roof model. Figure 5.7 presents both monitored and predicted indoor air temperature data as well as ambient air temperature collected from the meteorological station on the CSMC roof over the month of February.

As shown on Figure 5.7, the predicted indoor air temperature data from EnergyPlus fluctuate throughout the day, whereas the monitored indoor air temperature data remain more constant. This difference can be attributed to issues identified at the CSMC, such as malfunctioning of the watering system and plant death, especially during the month of February. Additionally, with exception of a few days in the middle of February, the ambient air temperature fluctuates in the same pattern as the predicted indoor air temperature from the model, providing more confidence in the modelling results.

The relationship between predicted and monitored indoor air temperature data is shown in Figure 5.8. There are times throughout the month of February where the predicted and monitored data closely align and other times where they are farther apart. The results of the calibration show that the total RMS error of the indoor air temperature for the month of February was ± 11 percent. The RMS error was calculated according to the method described in Section 4.5. The results meet the acceptable margin of error of ± 20 percent stated in Section 4.5. Overall, the green roof model seems to be able to predict the indoor air temperature more accurately during the summer months than in the winter months.

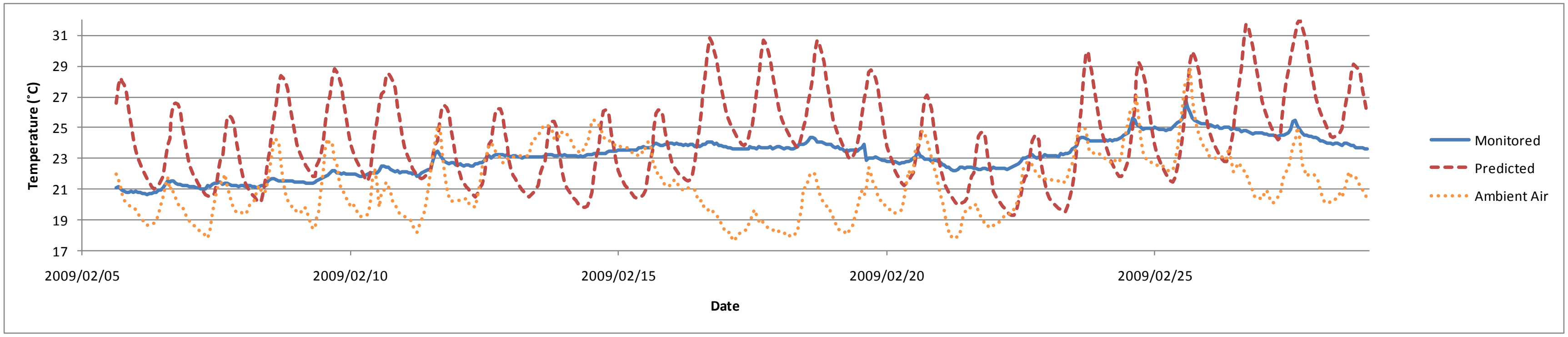


Figure 5.7: Monitored and Predicted Indoor Air Temperature Data below the Green Roof (February 2009)

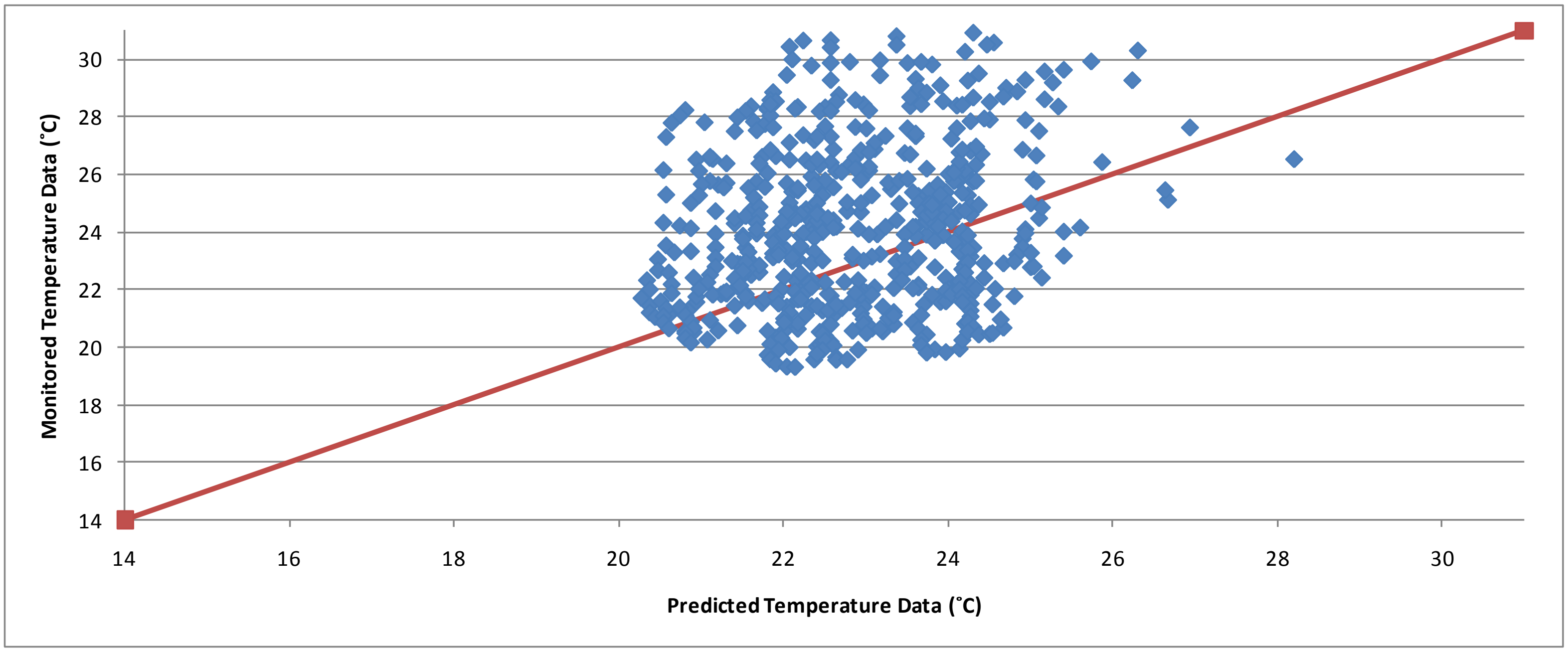


Figure 5.8: Correlation between Predicted and Modelled Indoor Air Temperature Data below the Green Roof (February 2009)

5.2 Green Roof Data Analysis

After determining the EnergyPlus green roof model was acceptable (Section 5.1), the outputs from the model were used to compare the potential benefit of having a green roof at the CSMC site to the original roof prior to green roof construction. This assessment was performed by comparing the maximum daily temperature (from hourly data) for the green roof against the original roof. The time the maximum temperature was reached was plotted to examine potential time shifting. Temperature duration curves were also plotted to assess the frequency at which temperatures were exceeded throughout the study period.

5.2.1 Roof Surface Temperature

The maximum temperature in a twenty-four hour period is referred to as the daily maximum temperature. Since monitored green roof surface temperature data are only available for June 2009, the results from that time period are presented and discussed here. Figure 5.9 shows that according to the model the predicted surface temperature of the original roof consistently exceeded the predicted surface temperature of the green roof for all 30 days in June, which is consistent with previous research reported by Simmons et al. (2008), Saiz et al. (2006), Liu & Minor (2005), Tan & Sia (2005), and Kohler (2002). Ninety percent of the time the predicted temperature of the original roof exceeded the monitored temperature of the green roof. The maximum predicted temperature of the original roof occurred on June 30th and was 69˚C, compared to a predicted temperature of 52˚C for the green roof on the same day, a 17˚C difference, which is consistent to what is found in literature as shown in Table 5.1.

Table 5.1: Summary of Green Roof Surface Temperature Results in Literature

Location	Summary of Results	Reference
Hong Kong (CSMC)	Green roof reduced surface temperature by 17˚C compared to a concrete roof	Section 5.2.1
Hong Kong (Oi Kwan)	Green roofs reduced surface temperature by approximately 15˚C	Section 3.3.1
Toronto	Green roofs reduced surface temperature by 20˚C	Liu & Minor (2005)
Singapore	Surface temperature of the green roof was 15˚C to 20˚C cooler than the concrete roof	Tan & Sia (2005)
Austin	Surface temperature of green roof was 30˚C to 37˚C cooler than black roof	Simmons et al. (2008)

Figure 5.9 also presents the ambient air temperature collected from the meteorological station on the CSMC roof during the month of June. The ambient air temperature and monitored green roof surface temperature generally follow the same temperature pattern throughout the month, showing confidence in the green roof surface temperature data collected in June.

Solar radiation dominates the energy balance of a roof. The original roof has low solar reflectivity, and therefore absorbs much of the solar radiation hitting the roof, resulting in high temperatures on the roof surface. Conversely, plants on green roofs reflect some of the solar radiation. Some of the radiation that is not reflected by plants is emitted from the soil surface as long-wave (thermal) radiation and sensible heat. Some of the solar radiation is also dissipated into the atmosphere through evapotranspiration (latent heat) from the soil and plant surfaces. Overall, a small amount of energy is absorbed by the soil which can then make its way into the building below (Sailor, 2008).

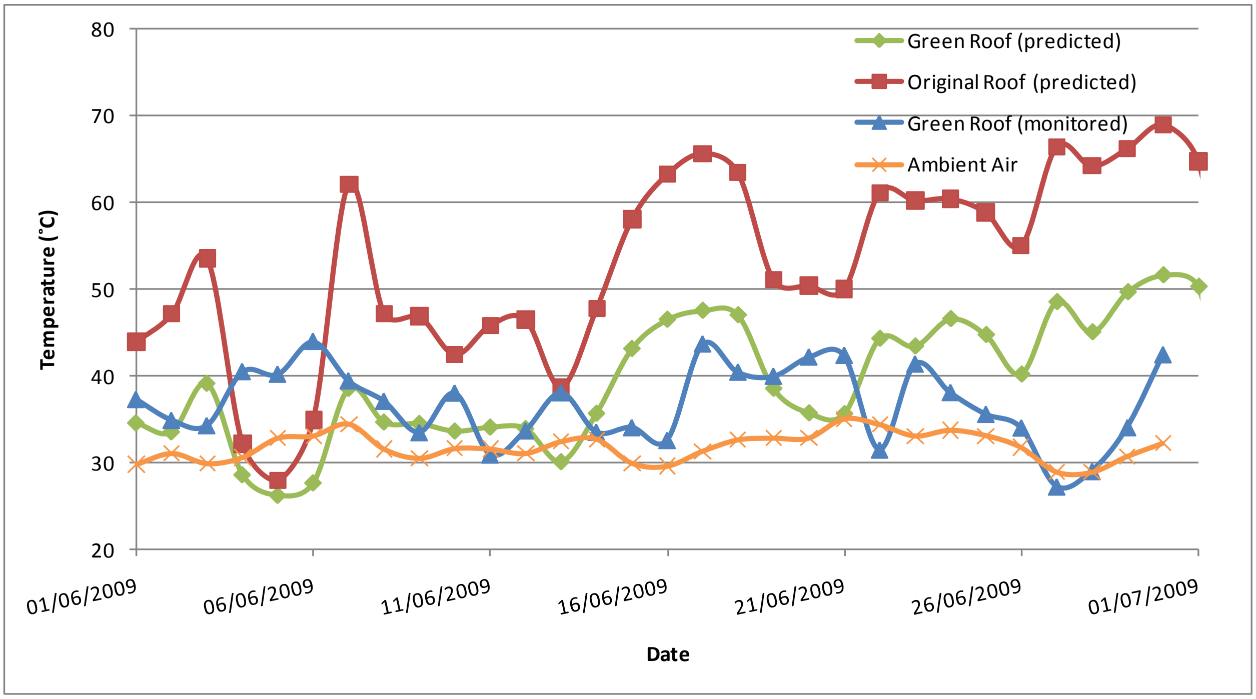


Figure 5.9: Maximum Daily Roof Surface Temperature (June 2009)

Figure 5.10 presents the frequency at which the maximum daily temperature is reached at a specific time. The green roof reaches its predicted maximum surface temperatures between 11:00am and 6:00pm, later than the original roof which reaches its maximum surface temperatures between 10:00am and 4:00pm. For the monitored data, the time at which the maximum temperature is reached is more spread out throughout the day – mainly between 9:00am and 4:00pm – than the predicted time from the green roof model.

The temperature duration curves in Figure 5.11 show the percentage of days in June 2009 that the green roof and original roof exceeded a certain temperature. Over the month of June, temperatures fluctuated on the original roof from 18˚C to 69˚C. Temperatures fluctuated on the green roof from 22˚C to 52˚C, a 21˚C smaller difference. Monitored temperatures on the green roof fluctuated between 24˚C and

36˚C. The original roof cools off quickly at night because of its low thermal mass; therefore easily emitting long-wave radiation. The green roof remains warmer at night because of stored energy. Overall, the green roof remains at a cooler and more consistent temperature than the original roof. Large temperature variation can decrease roof longevity. Frequent expansion and contraction can increase thermal stress potentially lead to cracking, resulting in more frequent maintenance and/or roof replacement. Maintaining a more constant temperature through installing green roofs can potentially improve roof longevity and reduce frequent maintenance (Johnston & Newton, 1996; Liu & Baskaran, 2004).

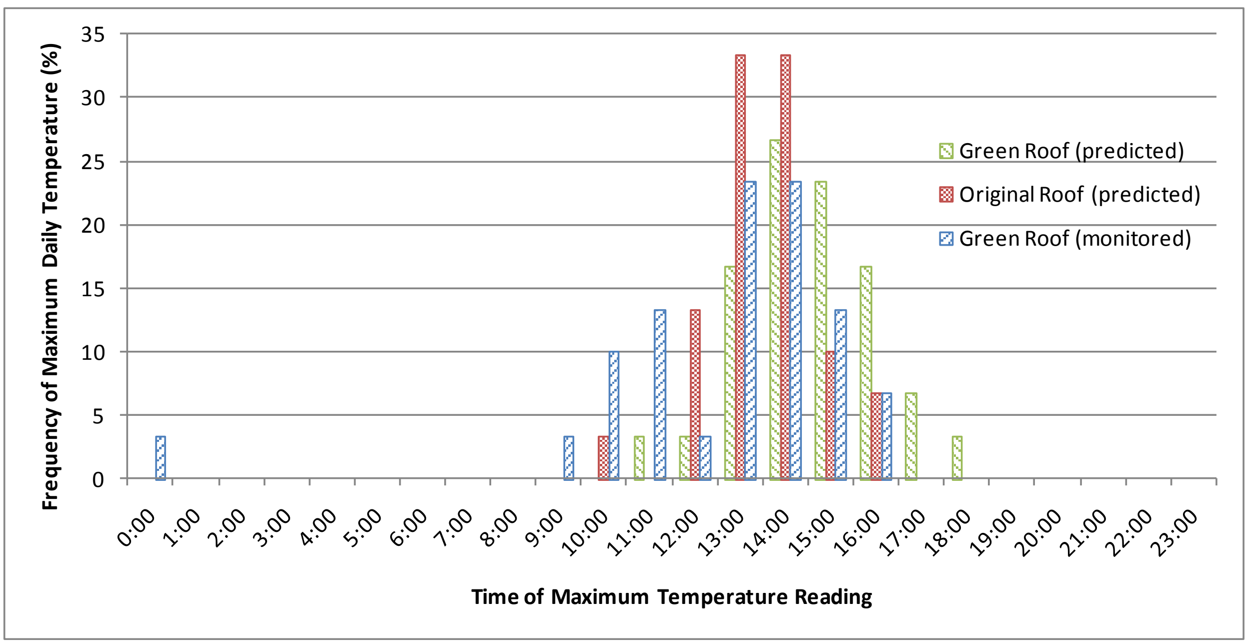


Figure 5.10: Frequency of Maximum Daily Surface Temperature at Specific Time of Day (June 2009)

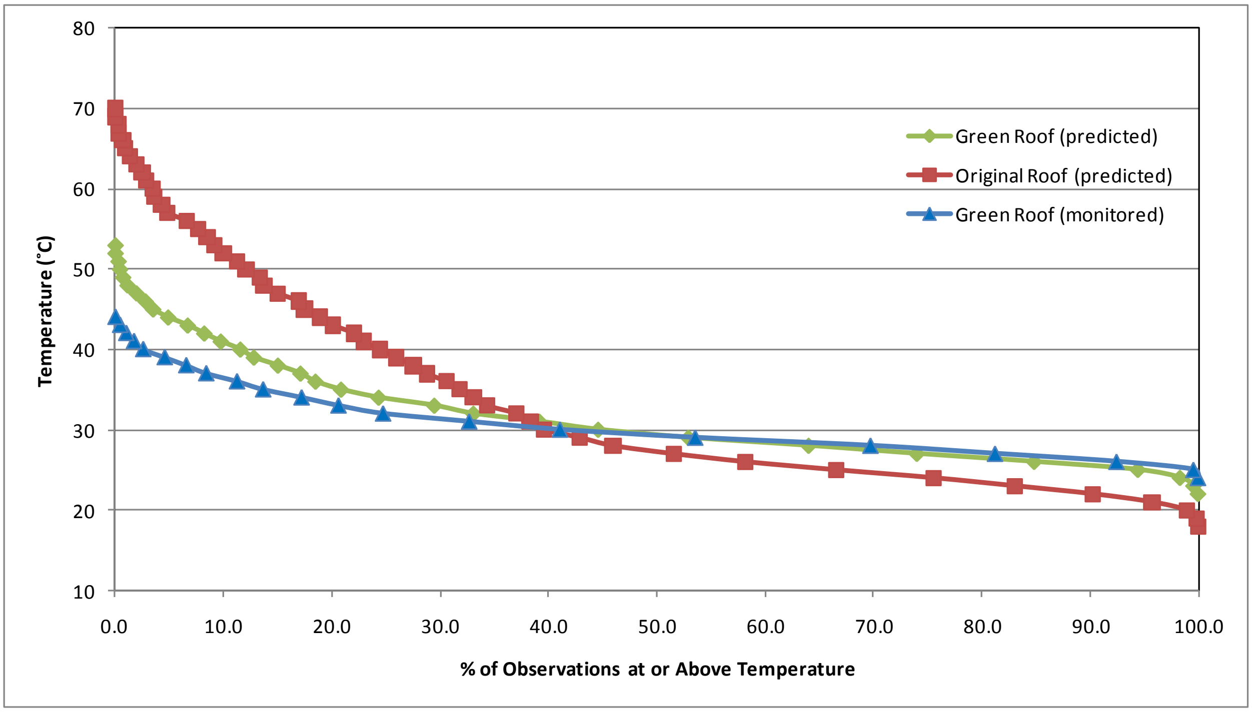


Figure 5.11: Temperature Duration Curves for Green Roof and Original Roof (June 2009)

5.2.2 Indoor Air Temperature

The predicted indoor air temperature for the rooms directly underneath the green roof was compared to the predicted indoor air temperature for the rooms directly underneath the original roof. In EnergyPlus the top floor was modelled as one open area instead of partitioned into separate rooms. The indoor air temperature was analyzed to determine if the green roof is effective in lowering the indoor air temperature. As shown on Figure 5.12, the predicted indoor air temperature under the green roof is between 0˚C and 3˚C cooler than the predicted indoor air temperature under the original roof. Figure 5.12 also presents the ambient air temperature collected from the meteorological station on the CSMC roof during the month of June. Throughout the month of June the temperature in the room below the original roof is above the ambient air temperature and the temperature in the room below the green roof is below the ambient air temperature. The green roof can help keep the room cooler than the outside temperature.

For 80 percent of the days in June, the monitored indoor air temperature under the green roof follows a similar pattern as the predicted temperature; however, the monitored temperature is not always below the predicted temperature of the room below the original roof. This difference can be attributed to the air conditioning in the room, which was modelled based on assumptions on the air conditioning system at CSMC. During a day where air conditioning was not used – on the weekend – the predicted and monitored indoor air temperatures follow the same pattern, where the temperature increases as the day progresses, peaks during midday and decreases towards night-time (Figure 5.13). The monitored temperature peaks at an earlier time than the predicted temperature, but at approximately the same temperature (31˚C), which is lower than the predicted temperature (34˚C) in the room under the original roof.

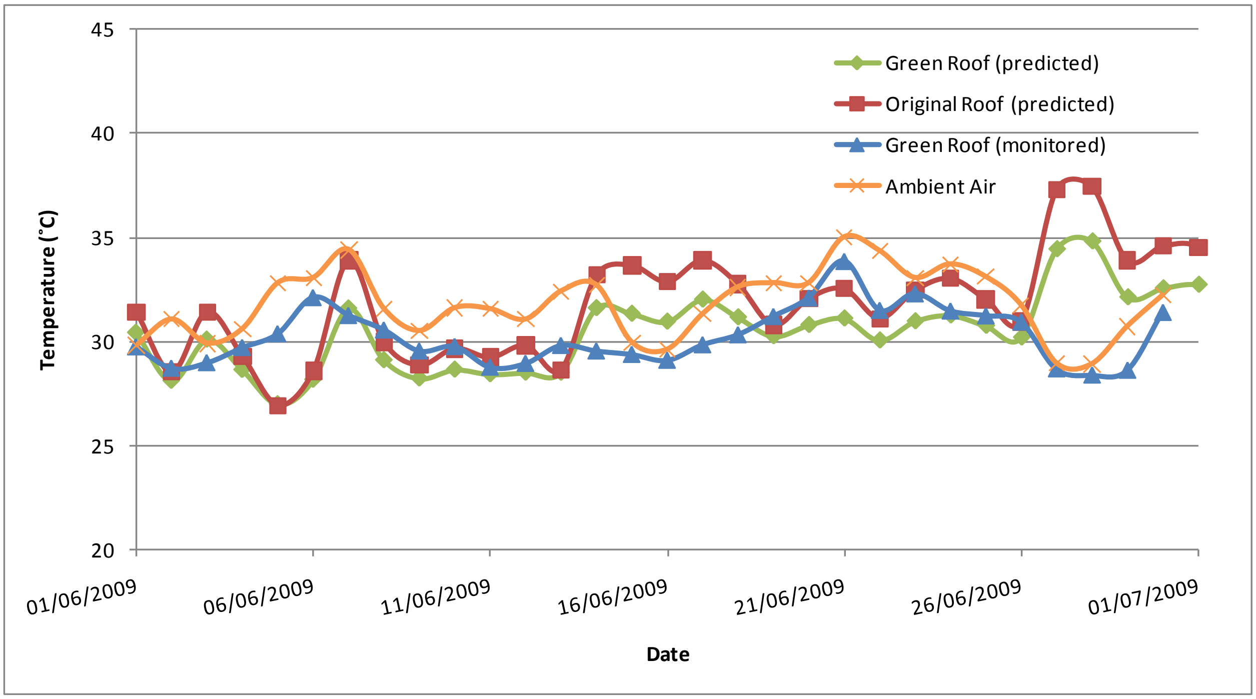


Figure 5.12: Maximum Daily Indoor Air Temperature (June 2009)

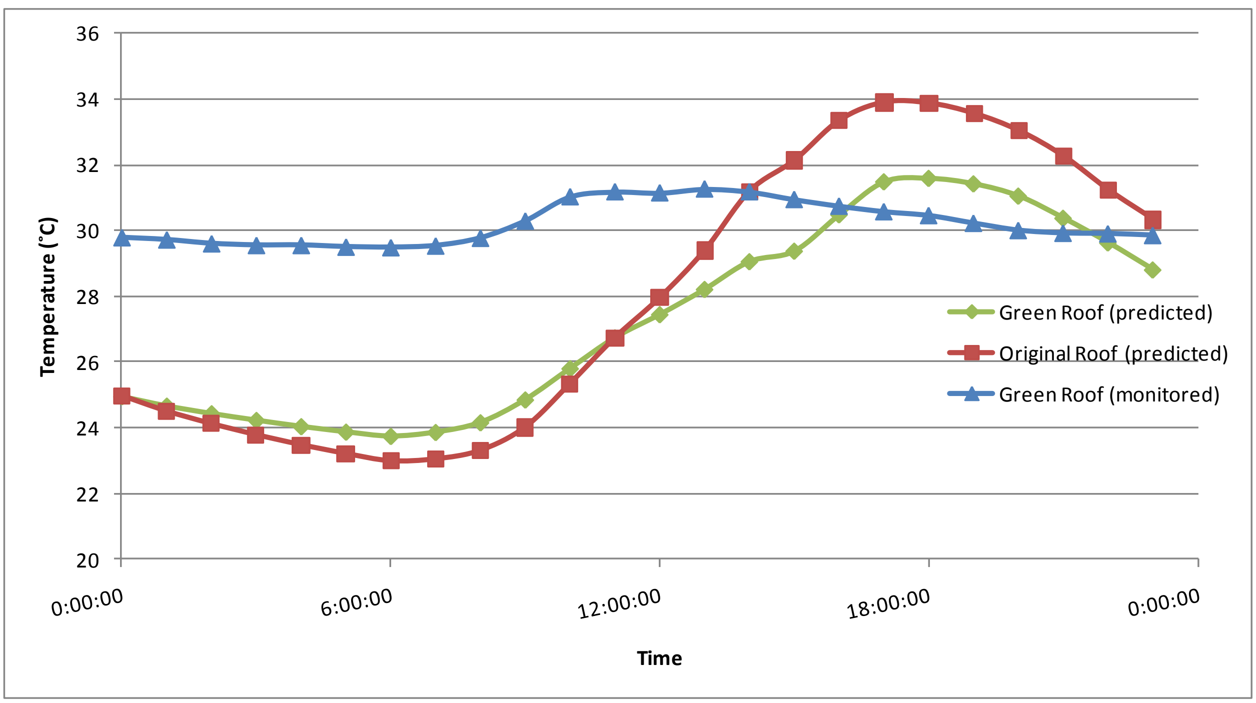


Figure 5.13: Hourly Indoor Air Temperature Data with No Air Conditioning (June 7, 2009)

The temperature duration curves (Figure 5.14) show that there is not an appreciable difference in the indoor air temperature fluctuations in the room below the green roof and original roof. This results from the use of air conditioning which maintains the temperature fairly constant. Comparison in HVAC energy usage is a more appropriate performance measure between the green roof and the original roof. Energy usage is discussed when comparing the energy consumption of various alternatives in Section 5.3.

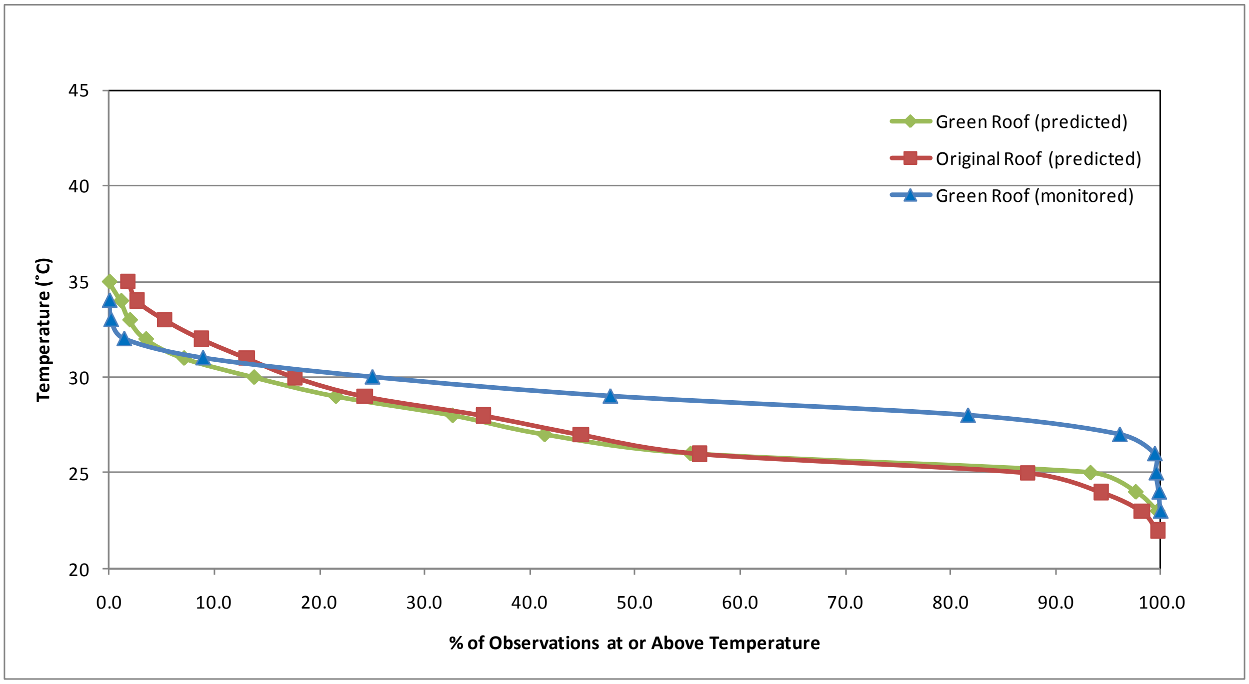


Figure 5.14: Temperature Duration Curves for Indoor Air below Green Roof and Original Roof (June 2009)

5.3 Comparison to Other Alternatives

As discussed in Section 4.6, the EnergyPlus building model was used to compare the performance of various alternatives to a green roof. Although green roofs have benefits other than energy savings, such as reduction in the urban heat island effect, reduction in storm water runoff, and increase in available green space, the alternatives were compared in terms of energy benefits. The alternatives assessed were a cool roof, an added insulation layer, and reflective windows. The performance measures assessed were temperature duration (for roof surface and indoor air), predicted monthly energy consumption and cost of various alternatives to a green roof. These alternatives were compared from April through September, the months where the CSMC building uses air conditioning. The specific details and inputs into the model are presented in Section 4.6. The results of the analysis are presented in the following sections.

5.3.1 Temperature Duration

The roof surface temperature was compared for the green roof, original roof, and cool roof. Roof insulation and reflective windows were only considered for their effects on indoor air temperature. The temperature duration curves from April to September (Figure 5.15 to Figure 5.20) show larger surface temperature fluctuations for the cool roof and original roof than for the green roof. In April, the green roof surface temperature fluctuates from 17˚C to 42˚C, a difference of 25˚C; the cool roof surface temperature fluctuates from 14˚C to 58˚C, a difference of 44˚C; and the original roof surface temperature fluctuates from 13˚C to 63˚C, a difference of 50˚C. The same pattern follows for the rest of the months with the temperature difference on the roof being greatest for the original roof, lowest for the green roof, and approximately in the middle for the cool roof.

The original roof has low thermal mass and cools quickly at night-time, giving off long-wave radiation. The cool roof has high solar reflectivity; therefore, it does not absorb as much solar radiation as the original roof, but it also cools down quickly at night. The green roof reflects much of the solar radiation, but the radiation that is absorbed by the soil is not easily released at night resulting in potentially higher temperatures at night-time than the original and cool roof.

In June, the temperature duration curve for the monitored green roof temperature data correlates well with the temperature duration curve for the predicted green roof temperature data.

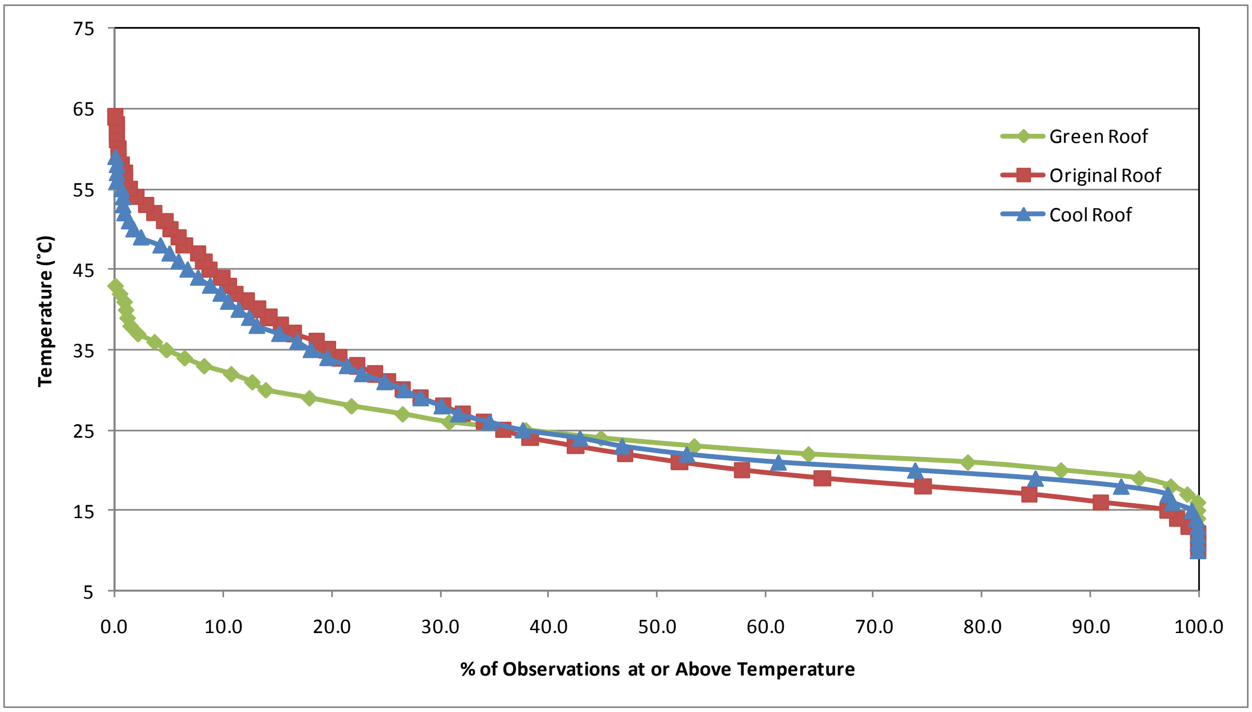


Figure 5.15: Surface Temperature Duration Curves for Various Alternatives (April 2009)

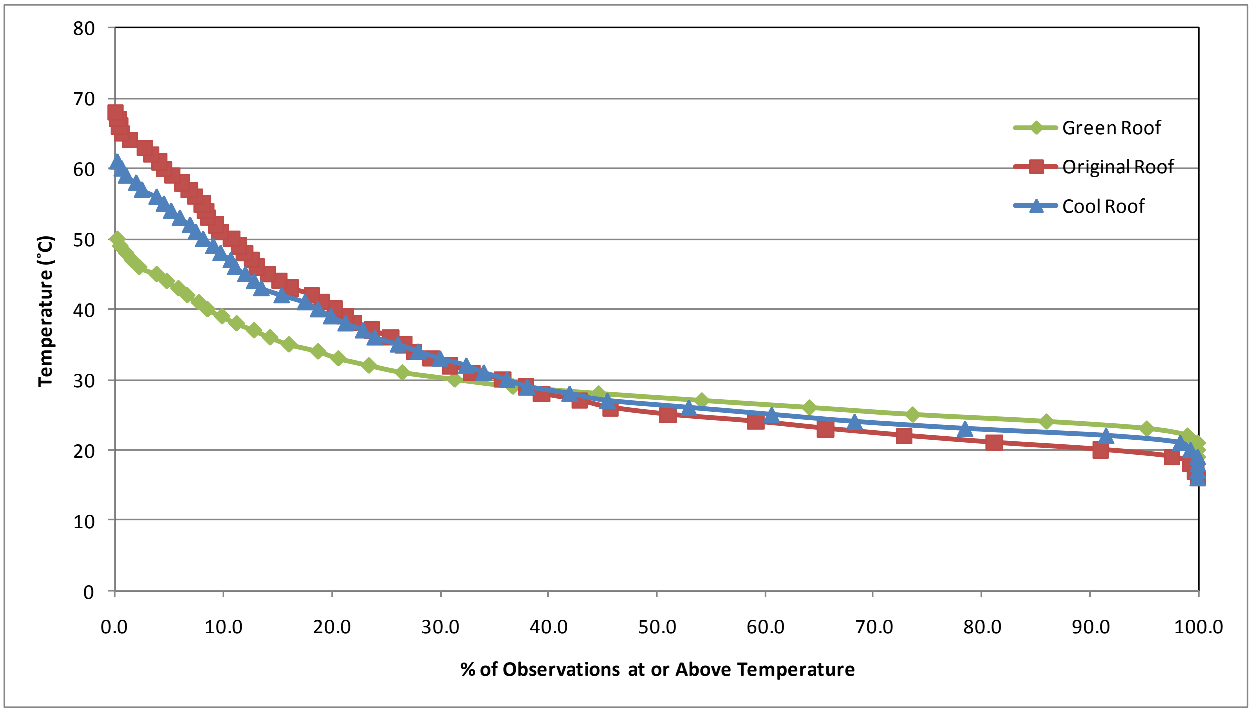


Figure 5.16: Surface Temperature Duration Curves for Various Alternatives (May 2009)

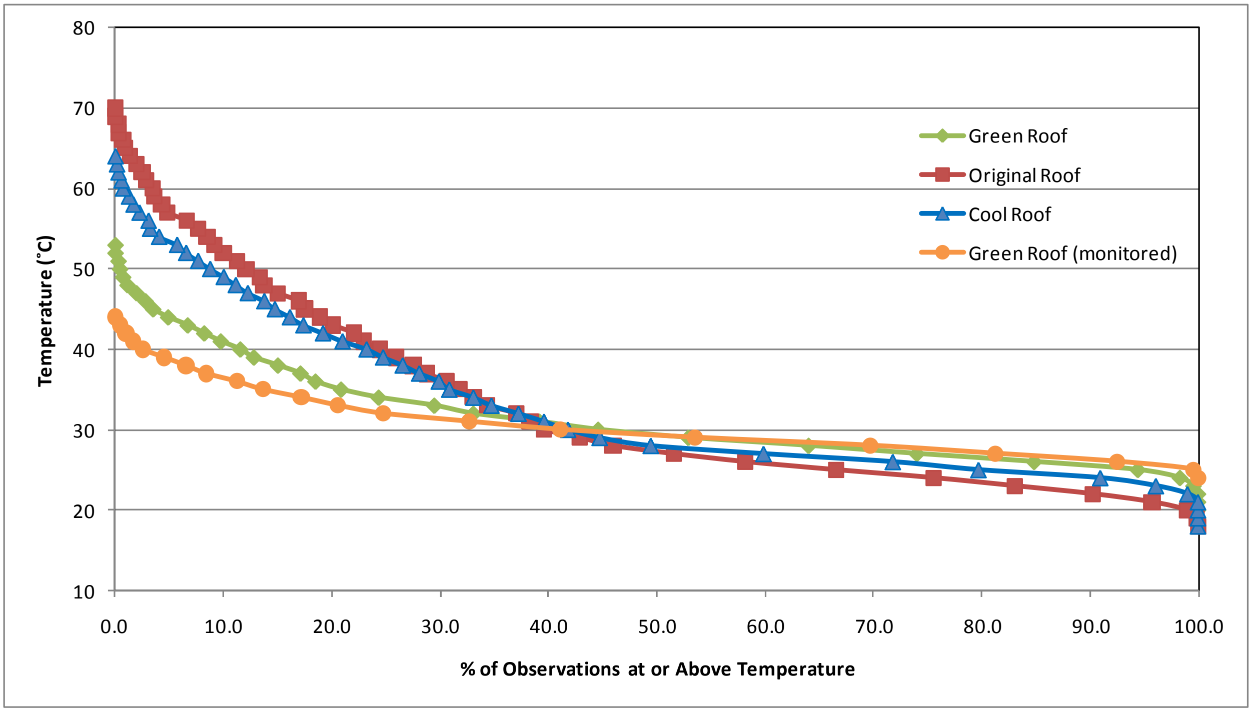


Figure 5.17: Surface Temperature Duration Curves for Various Alternatives (June 2009)

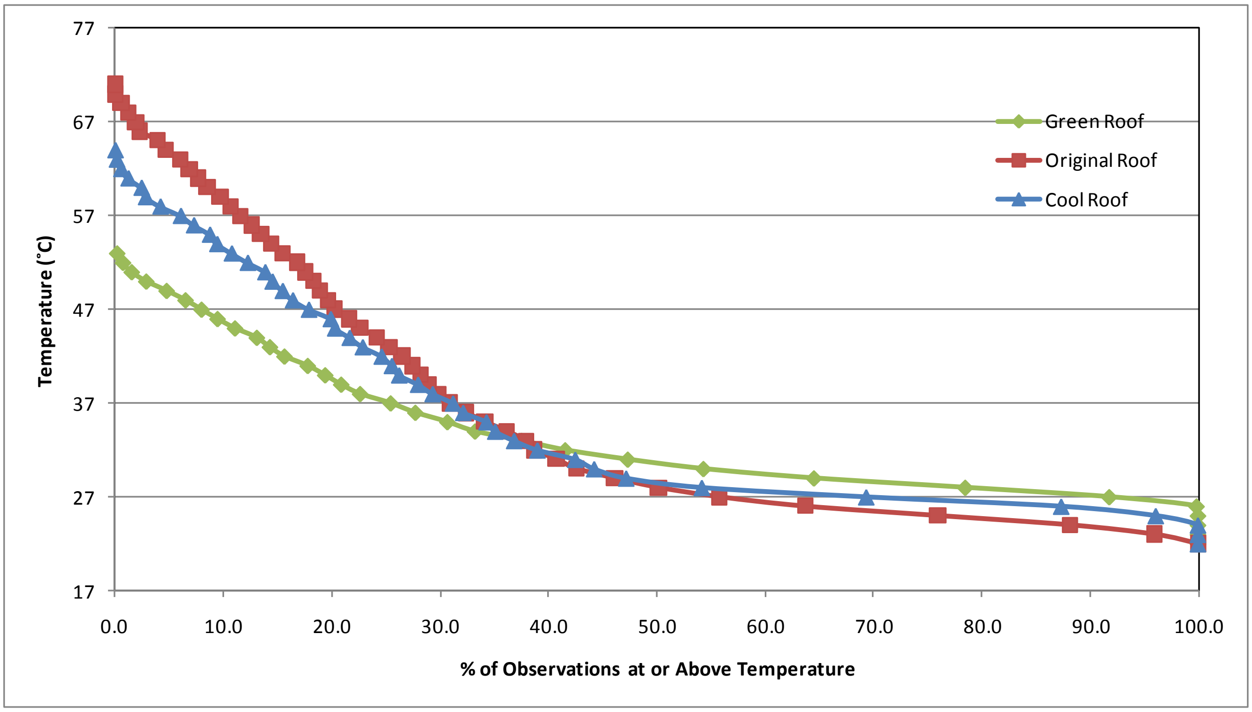


Figure 5.18: Surface Temperature Duration Curves for Various Alternatives (July 2009)

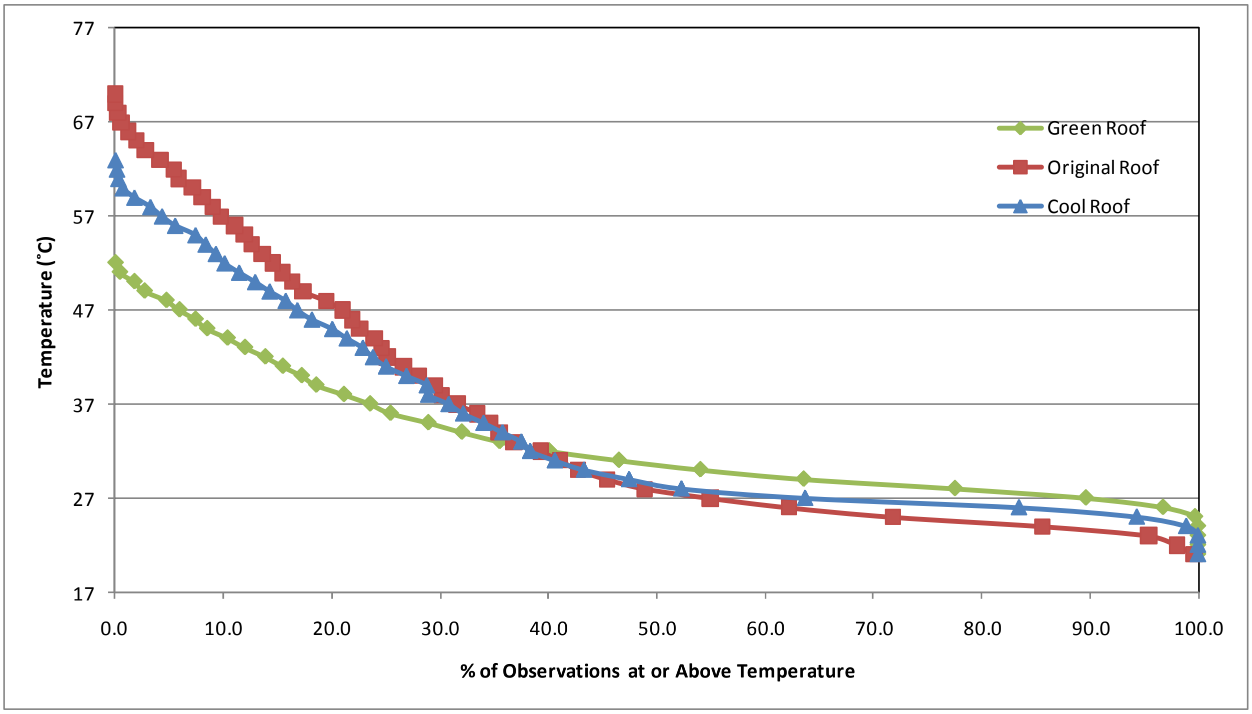


Figure 5.19: Surface Temperature Duration Curves for Various Alternatives (August 2009)

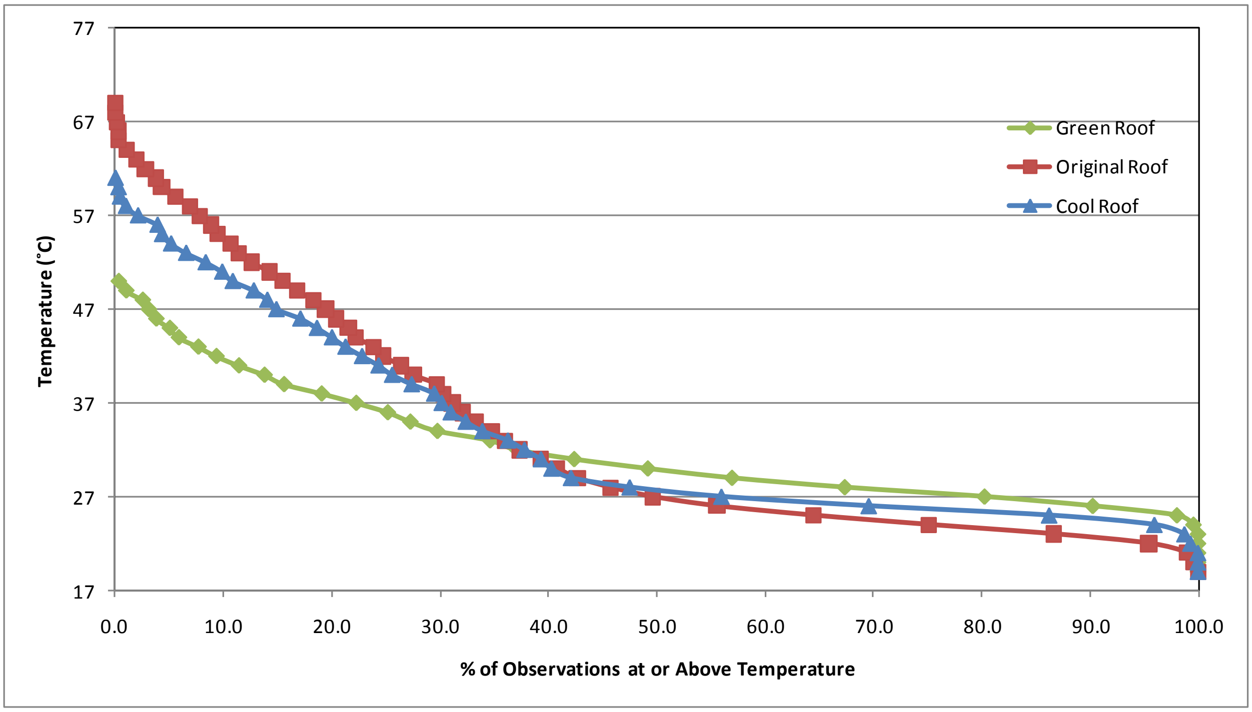


Figure 5.20: Surface Temperature Duration Curves for Various Alternatives (September 2009)

The indoor air temperature was compared for the green roof, original roof, cool roof, insulation layer, and reflective windows. The temperature duration curves (Figure 5.21 to Figure 5.26) from April to September show that the indoor temperature fluctuates the most under the original roof and with the reflective windows over the six month period. The indoor temperature fluctuates the least under the cool roof, followed by added roof insulation, and then green roof. This pattern follows for all of the months where air conditioning is used, except for April where there is minimal difference between the temperature duration of the cool roof, green roof, and roof insulation layer.

The indoor air temperature results do not correlate with the roof surface temperature results. For the roof temperature, the green roof surface temperature fluctuates less than the cool roof surface temperature; however, for the indoor air temperature, the temperature in the room below the cool roof remains more constant than the temperature in the room below the green roof over the six month study period where air conditioning was used. Although the temperature in the room under the cool roof was more constant than the temperature in the room under the green roof, this difference was only by approximately 1˚C.

Conclusions on the comparison of the various alternatives is difficult to make when looking at the temperature differences alone because of the air conditioning which set the indoor air temperature at 26˚C during weekdays from 8:00am until 7:00pm. In the next section the monthly energy consumption of the HVAC system for the various alternatives is discussed in order to provide a better understanding on the most feasible alternative.

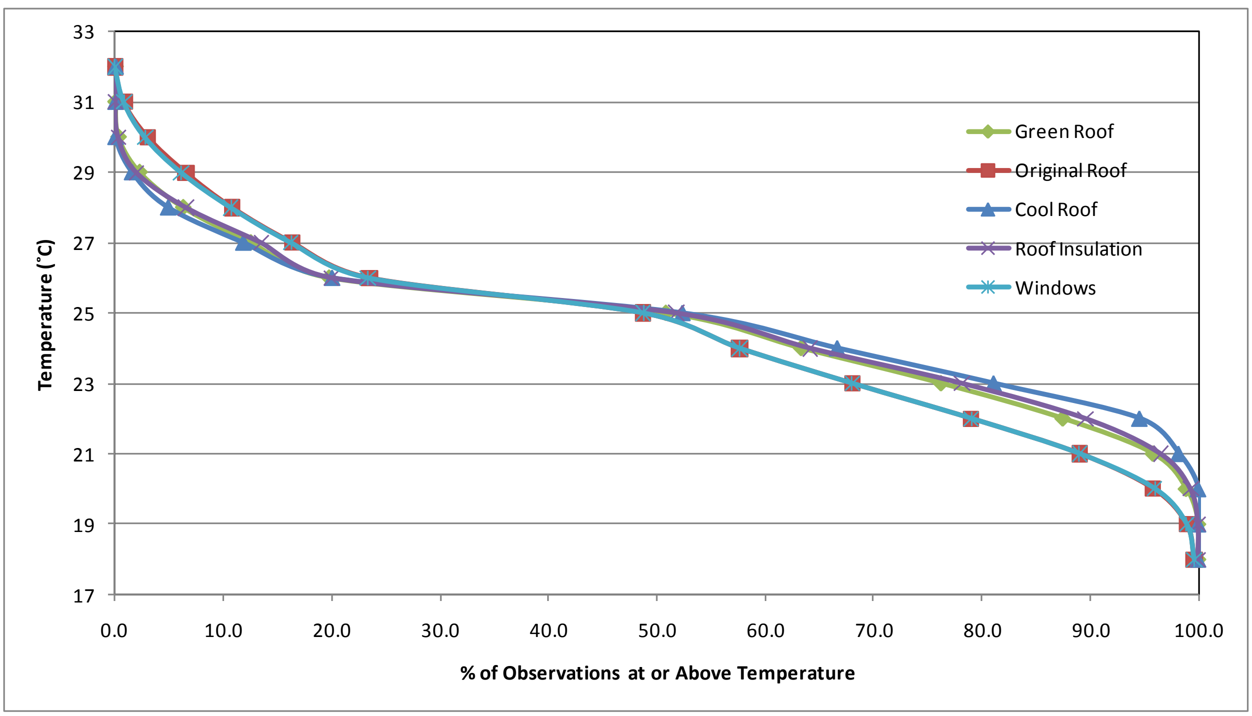


Figure 5.21: Indoor Air Temperature Duration Curves for Various Alternatives (April 2009)

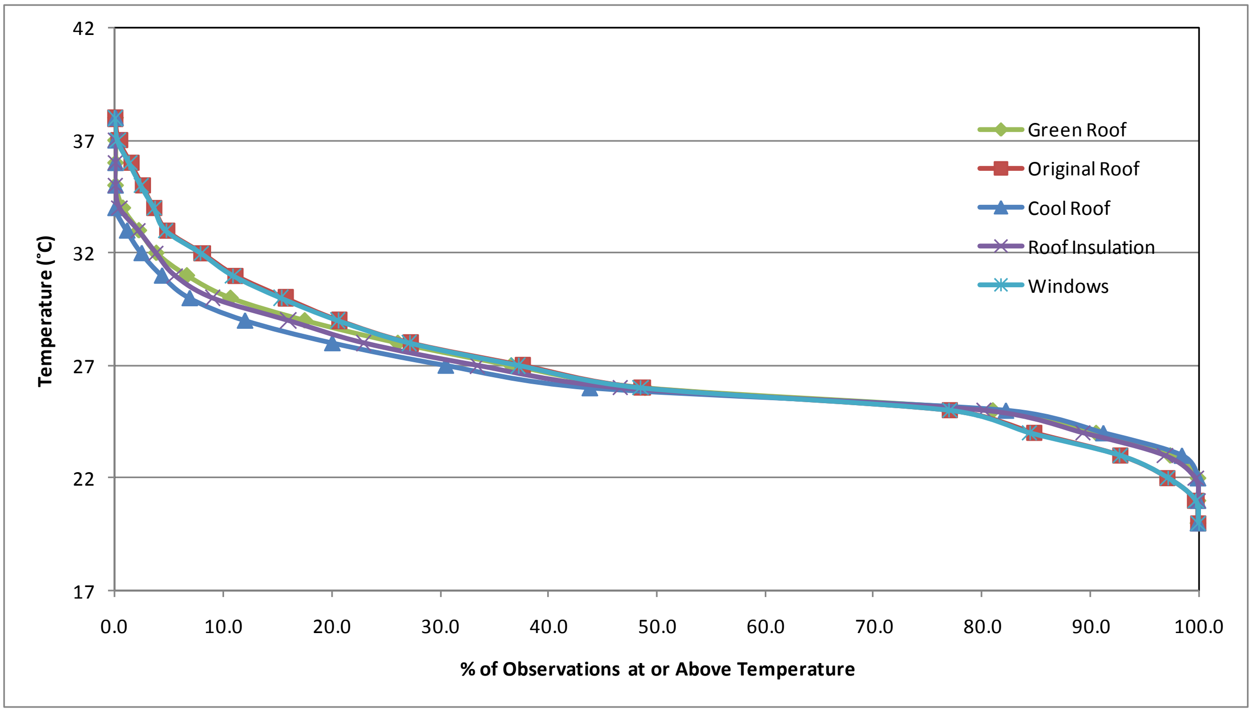


Figure 5.22: Indoor Air Temperature Duration Curves for Various Alternatives (May 2009)

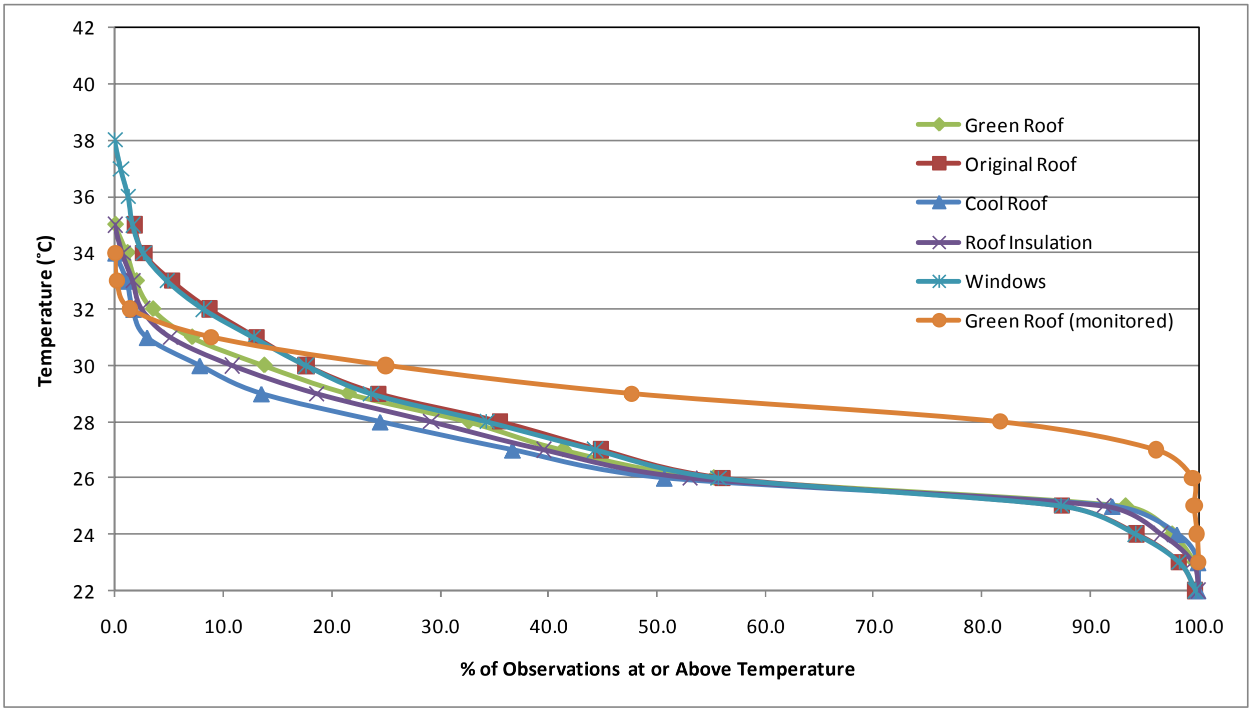


Figure 5.23: Indoor Air Temperature Duration Curves for Various Alternatives (June 2009)

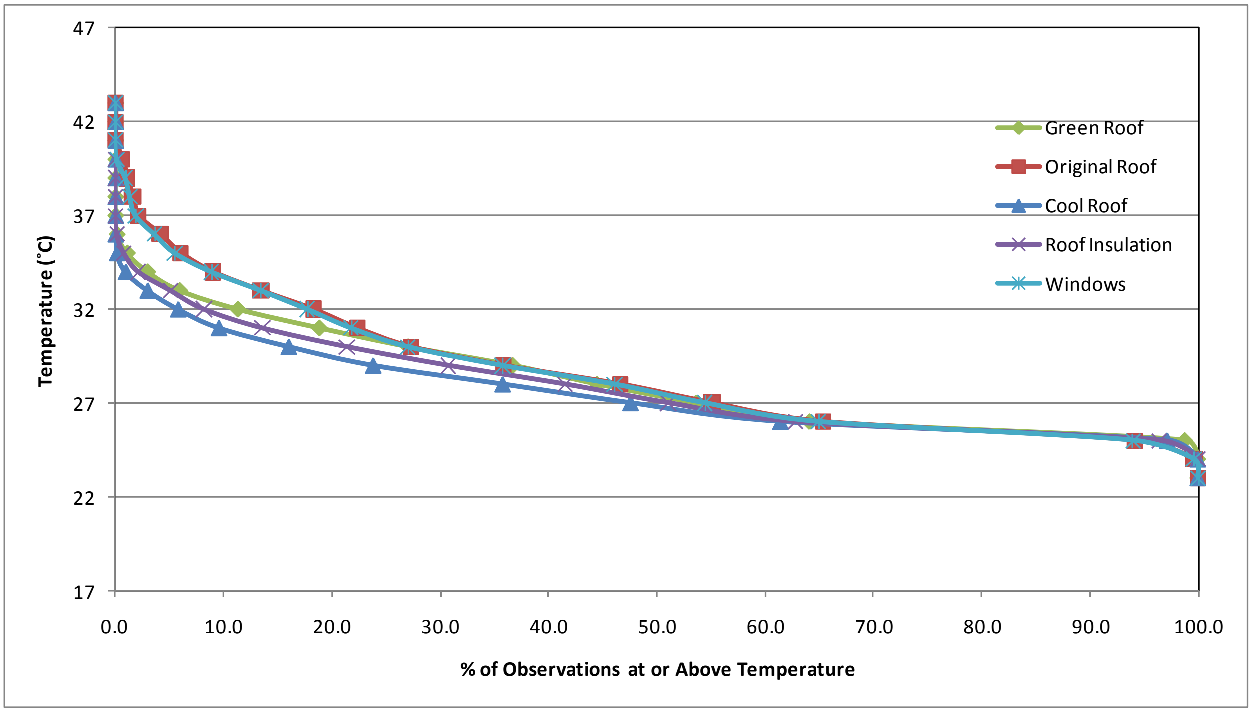


Figure 5.24: Indoor Air Temperature Duration Curves for Various Alternatives (July 2009)

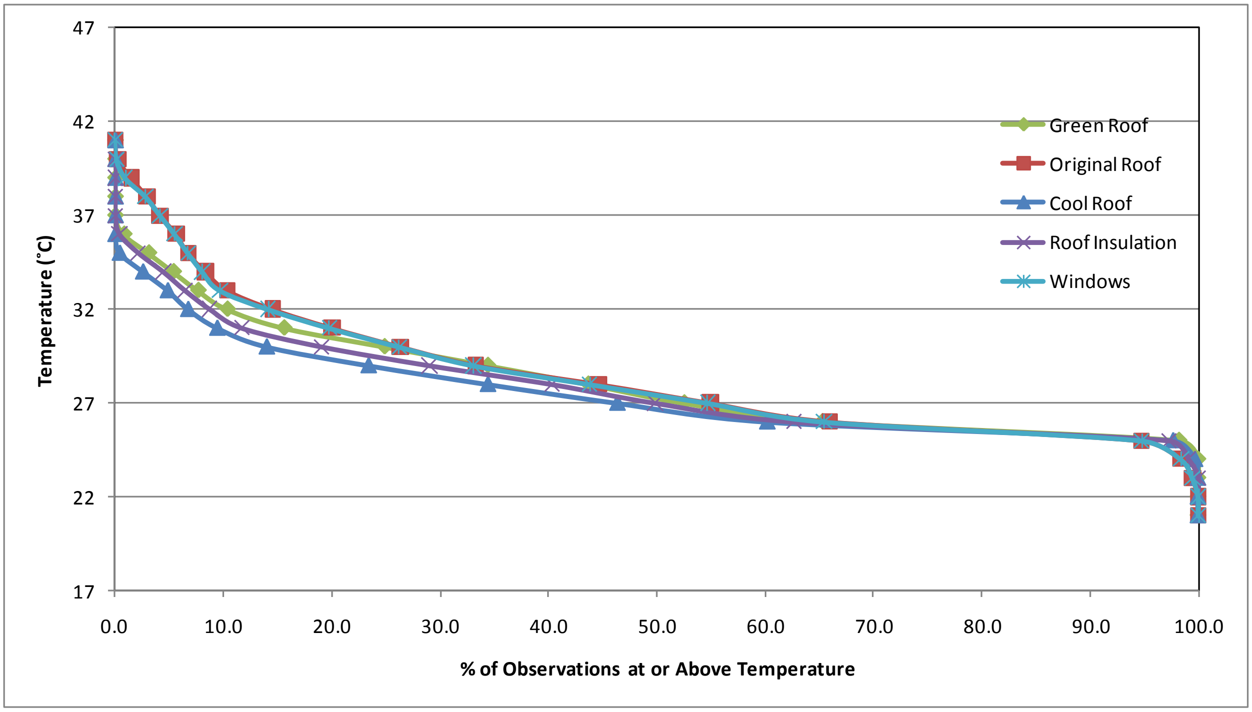


Figure 5.25: Indoor Air Temperature Duration Curves for Various Alternatives (August 2009)

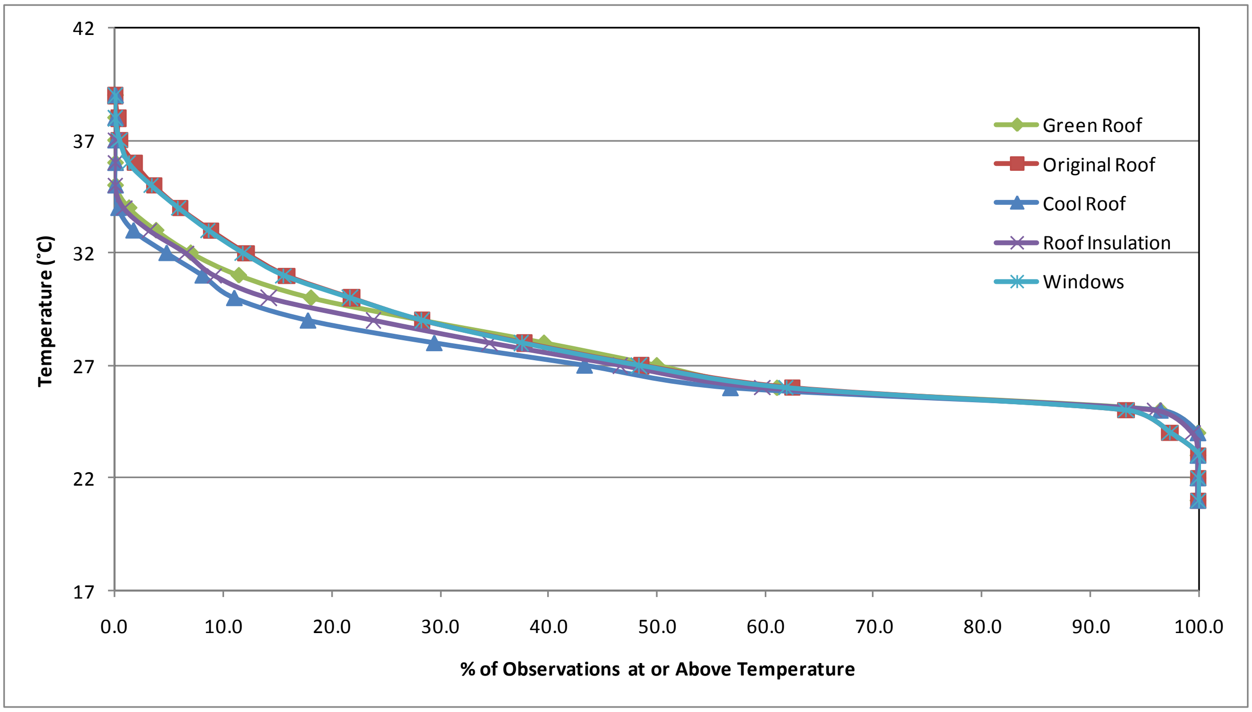


Figure 5.26: Indoor Air Temperature Duration Curves for Various Alternatives (September 2009)

5.3.2 Energy and Cost Comparison

This section discusses the monthly HVAC energy usage and associated cost for the green roof, original roof, cool roof, roof insulation, and reflective windows over the six month period from April to September, when air conditioning is used. HVAC usage is based on the assumption that air conditioning is used five days a week from 8:00am until 7:00pm, on the top floor of the CSMC building. For the purposes of this analysis, cost is defined in terms of construction, operation, and maintenance costs only. The replacement frequency for each alternative is also considered. All cost values are reported in Canadian dollars. For the green roof, the cost of irrigation is included in the calculations based on a rate of $0.51/m^3 (Water Supplies Department, 2011). The electricity cost is $0.15/kWh (HK Electric, 2011).

Table 5.2 presents a summary of the monthly energy usage (in kWh) in the top floor of the CSMC building. Figure 5.27 and Figure 5.28 summarize HVAC energy usage and associated operational cost (including irrigation for the green roof) in bar graphs. The annual HVAC energy usage for the green roof is 2592 kWh +/- 437 kWh/199 kWh. The uncertainty is based on differences in conductivity values for the building construction material (concrete). The cost associated with the HVAC energy usage (including irrigation cost) for the green roof is $420.69 +/- $53/$24.

Table 5.2: Summary of HVAC Energy Consumption and Operational Cost for Various Alternatives

	HVAC Energy Consumption (kWh)				
Month	**Original Roof**	**Green Roof**	**Cool Roof**	**Roof Insulation**	**Reflective Windows**
April	268.3	210.6	209.9	217.3	262.9
May	393.3	347.9	329.9	343.3	387.8
June	535.2	503.0	462.9	484.1	527.9
July	553.1	525.0	481.4	503.8	546.6
Aug	604.5	569.8	518.3	546.1	596.2
Sept	468.7	435.2	405.0	422.7	461.6
Total	**2823.1**	**2591.5**	**2407.4**	**2517.4**	**2783.0**

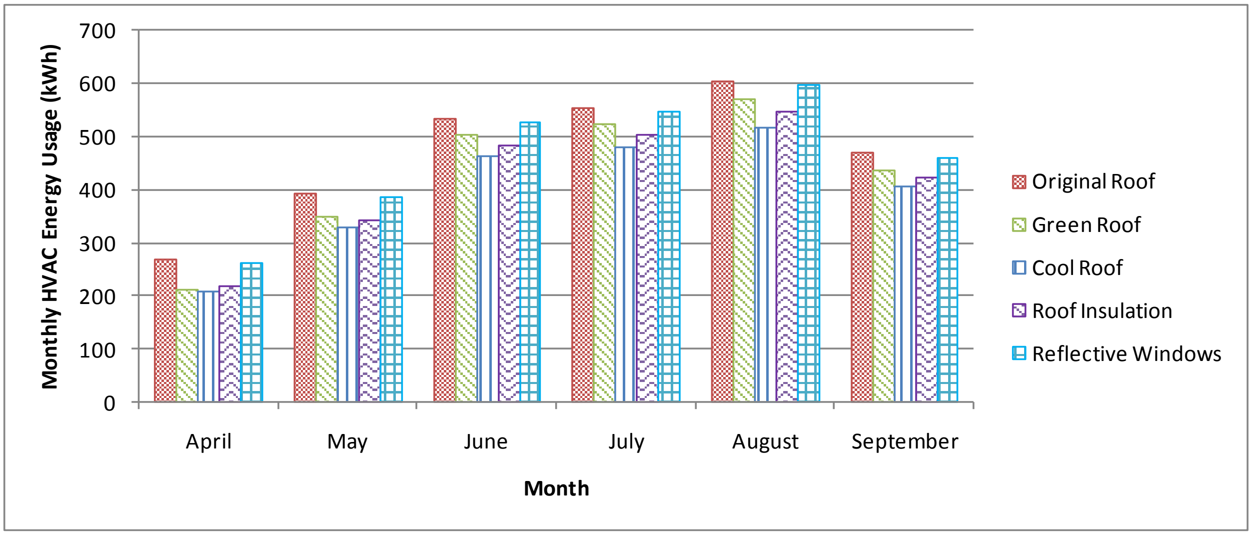


Figure 5.27: Monthly HVAC Energy Consumption for Various Alternatives

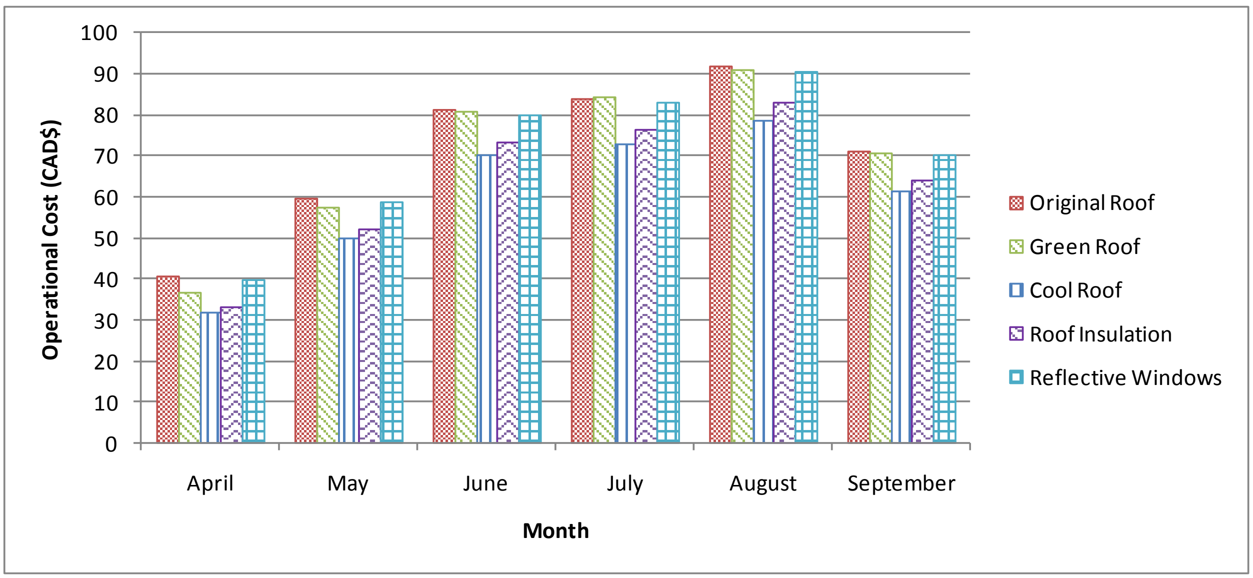


Figure 5.28: Monthly Operational Cost for Various Alternatives

Over the six month period the cool roof consumes the least amount of energy. In total, the cool roof uses 184 kWh less than the green roof, 110 kWh less than the added roof insulation, 376 kWh less than the reflective windows and 416 kWh less than the original roof. The cool roof is the most energy efficient option for the entire six month period, although the difference is more significant during the hotter months of June, July, and August. The green roof may require more energy to cool the building than the cool roof because the insulation provided by the soil layer prevents the green roof from cooling down at night to a temperature as low as the cool roof. As such, more energy would be required to cool the room underneath the green roof to a specified temperature than the room underneath the cool roof.

With respect to operational cost (HVAC energy usage), the cool roof is also the most cost efficient alternative. Over the six month period, the cool roof costs $55 less than the green roof, $17 less than roof insulation, $57 less than reflective windows, and $63 less than the original roof. The added cost of roof irrigation contributes to the green roof becoming less cost effective during the operational period of the building.

Cost benefit analysis (CBA) is a decision making tool used to weigh several alternatives to determine which is worth pursuing. CBA quantifies both cost and benefits in terms of dollar value – expressed as net present value including a discount rate (City of Toronto & OCE-ETech, 2005). A full CBA was not conducted. Rather, a life cycle cost assessment was conducted that looked at construction, maintenance, HVAC energy usage, and replacement costs for the following alternatives:

- original roof only;
- green roof only;
- original roof with reflective layer (cool roof); and
- original roof with added insulation.

Since reflective windows do not seem to provide greater energy savings than the original roof during the operational phase, reflective windows were not included in the life cycle cost assessment. Evaluating the benefits of each alternative in terms of economically relevant factors was outside the scope of this thesis; however, a full CBA would be beneficial in future research on the viability of different alternatives for reducing energy consumption of buildings, as discussed in Section 6.2.

Adams & Marriott (2008) reported that in Portland a conventional roof has a construction cost of \$107.64/m^2 and a green roof with minimal soil and vegetation has a construction cost of \$169.53/m^2. Maintenance for a green roof would involve visual inspection twice yearly, plant and irrigation maintenance and costs approximately \$0.27/m^2. Maintenance for a conventional roof would also occur twice yearly and costs approximately \$0.11/m^2 (Adams & Marriott, 2008). Townshend (2007) reported that in Hong Kong an extensive green roof costs between \$49 and \$122/m^2. Maintenance costs for an extensive green roof in Hong Kong range from \$0.10/m^2 per year and \$0.28/m^2 per year. For the green roof, local costs as estimated by Townshend (2007) are used in this life cycle cost assessment.

Initial cost of a cool roof ranges from \$8.07/m^2 to \$16.15/m^2 on top of the cost of a conventional roof. Maintenance involves occasional washing of the roof to maintain solar reflectivity of the coating (U.S. EPA, 2008). A cool roof needs to be replaced after approximately 20 years (Environmental and Energy Study Institute, 2011). Polyiso insulation costs approximately \$34.12/m^2 (Zero By Degrees, 2009). Reflective windows cost between \$40 and \$60 per window (PowerHouse, 2011).

The cost selected for each alternative is outlined in Table 5.3. Local Hong Kong costs are available for the green roof only. Costs used for alternatives are taken from other regions and are provided for comparison purposes. The discount rate used in order to calculate the net present value was the prime rate in Hong Kong of 5.25% (Public Bank Hong Kong, 2011). A 40 year time horizon was used. Figure 5.29 shows the net present value for each alternative over a 40 year time horizon. Figure 5.29 shows that after 20 years the green roof becomes more financially viable than the alternatives. This is mainly due to the replacement frequency of the green roof, which is 40 years, compared to 20 years for all of the alternatives.

Table 5.3: Summary of Costs for Each Alternative

Alternative	Construction Cost	Maintenance Cost (Annual)	HVAC Energy Cost (Annual)	Replacement Frequency (yrs)
Original Roof	$23,680.80	$48.40	$428.58	20
Green Roof	$26,912.60	$61.60	$420.69	40
Original Roof + Reflective Layer	$27,233.80	$48.40	$365.48	20
Original Roof + Insulation Layer	$31,187.20	$48.40	$382.17	20

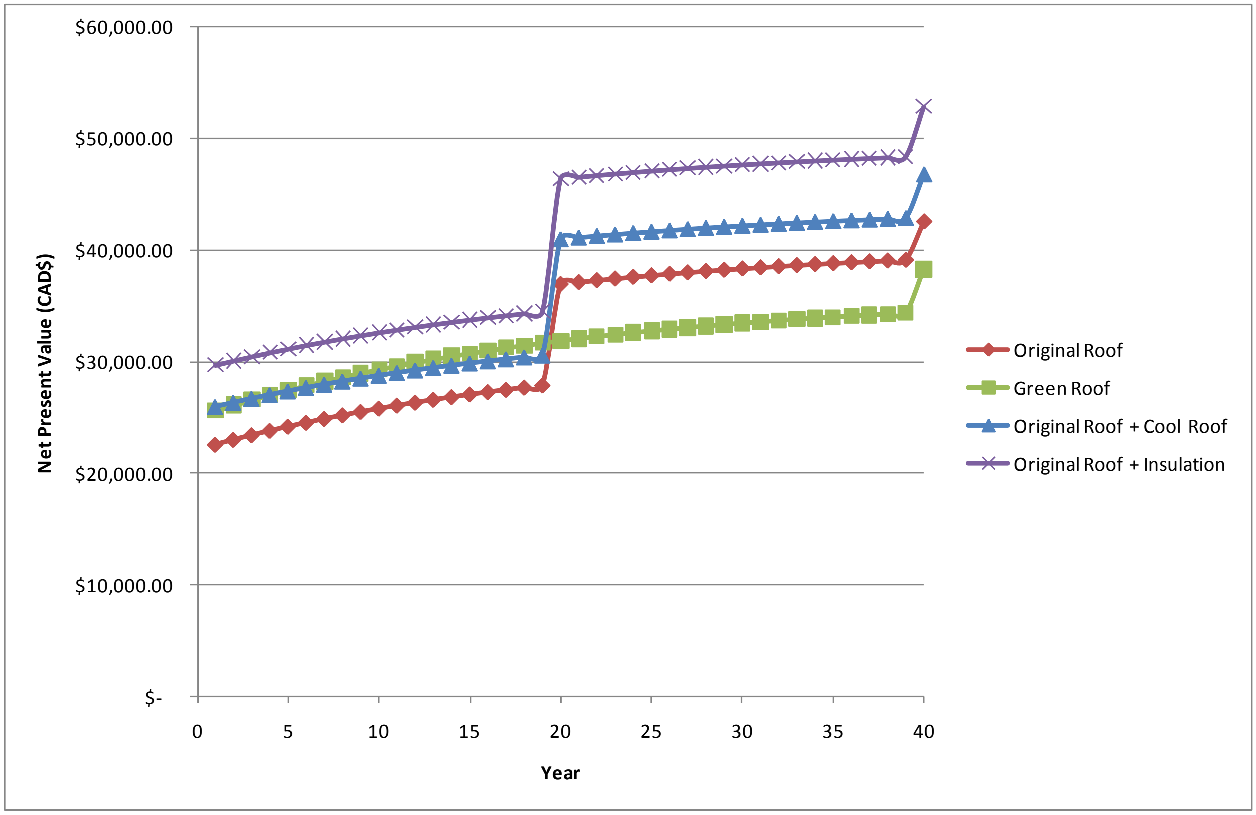


Figure 5.29: Net Present Value of Alternatives Over 40 Year Time Horizon

5.3.2.1 Comparison to Existing Energy Bills

Energy bills from the top floor of the CSMC building are available for April to July 2009. Table 5.4 provides a comparison of the predicted cost of HVAC from the EnergyPlus CSMC green roof model to the existing energy bills. According to the EnergyPlus CSMC green roof model approximately 52 percent of the energy consumption goes towards the HVAC system, with the remainder attributed to lighting. This does not factor in electricity usage from computers and other appliances. However, assuming the HVAC system comprises approximately 52 percent of the energy bill, the predicted cost does correlate with the actual cost obtained from the energy bills during May and July.

Table 5.4: Comparison of Predicted HVAC Cost to Actual Cost

Month	Actual Electricity Bill (CAD$)	Operational Cost from Electricity Bill (CAD$)[1]	Operational Cost from EnergyPlus Model (CAD$)
April	154.01	80.09	36.69
May	91.38	47.52	57.46
June	237.32	123.41	80.81
July	136.89	71.18	84.23

1. Assumed to be 52% of electricity bill.

5.4 Green Roof Irrigation

Since green roof irrigation does contribute to the operational cost of the green roof, the sensitivity of the irrigation schedule was analyzed to determine if reducing the amount of irrigation affected overall green roof performance. In the base case, the green roof was irrigated daily at 8:00am and 8:00pm for approximately one hour and 0.7 mm per watering period. A "smart schedule" was used which only irrigates the green roof if soil moisture is below 30 percent. Based on the above scenario the total water used from April to September was 53.8 m^3. The following alternate irrigation schedules were investigated:

- irrigation once daily at 8:00am (0.7 mm for 1 hour);
- irrigation twice daily at 8:00am and 8:00pm (0.35 mm for 1 hour each);
- irrigation once daily at 8:00am (0.35 mm for 1 hour); and
- no irrigation.

Figure 5.30 shows that irrigation has minimal impact on the overall HVAC energy performance and operational cost. When less water was used for irrigation the water cost decreased, but the overall HVAC energy usage increased; therefore, the overall cost was not impacted significantly as shown in Figure 5.30. Overall, the number of watering times a day and amount of irrigation do not strongly influence the total cost associated with operating the building.

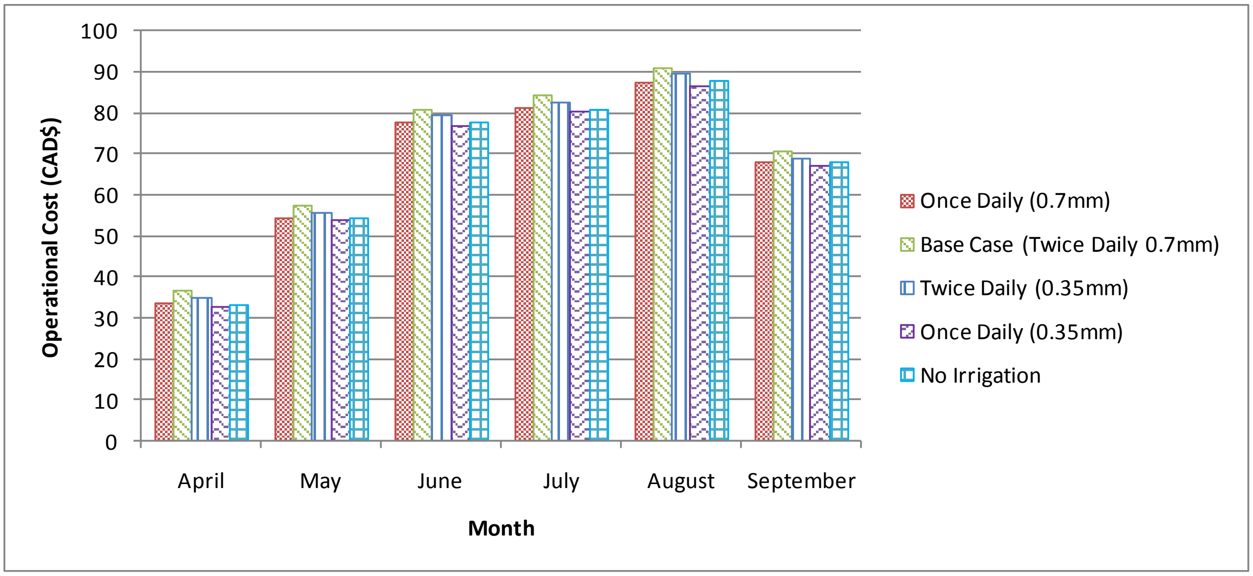


Figure 5.30: Monthly Operational Cost for Different Irrigation Amounts

Chapter 6 – Conclusions and Recommendations

6.1 Conclusions

In order to investigate and estimate the potential energy benefits of installing extensive green roofs on buildings in Hong Kong two case studies of extensive green roofs were analyzed. The Oi Kwan case study not only compared the thermal performance of green roofs to a typical concrete roof, but assessed the performance between different types of green roofs. The study concluded that green roofs were successful in reducing roof surface temperatures, delaying the time at which the maximum surface temperature is reached, and contributing to a cooler indoor air temperature for the room directly below the green roof. Additionally, using a combination of plants and rock wool in the substrate layer improved green roof thermal performance. In order to quantify potential energy savings to building owners in Hong Kong, as well as assess other performance measures, a numerical model is beneficial. Since data were limited in the Oi Kwan study, the CSMC green roof was used for numerical model development and subsequent data analysis. The CSMC green roof not only looked at surface and indoor air temperature reductions from using a green roof instead of the original roof, but also quantified these reductions in terms of energy and cost savings.

EnergyPlus was successfully used to model the two-storey CSMC building in downtown Hong Kong with its existing green roof and its previous concrete roof. The building was simplified by focusing the modelling on the top storey and assuming the floor was one open room. EnergyPlus is a useful building energy simulation model; however, it has a steep learning curve. One benefit of the program is that it has a built-in “eco roof” function. Additionally, once the building model is complete, it is more straight-forward to modify specific parameters such as replacing the green roof with a cool roof or changing the irrigation schedule for the green roof.

For model calibration, monitored temperature data were compared to predicted temperature data from the EnergyPlus model during June, a summer month when air conditioning was used, and February, a winter month where air conditioning was not used. For June, the results of the calibration show that the total RMS error of the roof surface temperature and the indoor air temperature were ± 16 percent and ± 10 percent, respectively. For February, the results of the calibration show that the total RMS error of the indoor air temperature was ± 11 percent. The predicted temperature data met the monitored temperature data within the acceptable margin of error of ± 20 percent, showing that the simplifying assumptions were valid.

The green roof was compared to the original roof by assessing the following performance measures: maximum daily temperature, time at which maximum temperature was reached, and temperature duration (for roof surface and indoor air). The performance of the green roof was also compared to the original roof, cool roof, roof insulation, and reflective windows by evaluating the temperature duration (for roof surface and indoor air), predicted monthly energy consumption and associated operational cost for each alternative. A life cycle cost assessment was also conducted that looked at construction, maintenance, HVAC energy usage, and replacement costs. The main conclusions of this thesis are:

- During the summer month of June, the monitored and predicted surface temperature of the green roof at the CSMC was consistently below the predicted surface temperature of the original roof. The maximum predicted temperature of the original roof occurred on June 30th and was 69˚C, compared to a predicted temperature of 52˚C for the green roof on the same day.

- The green roof model shows time-shifting as to the time of day that the green roof reaches its maximum surface temperature (between 11:00am and 6:00pm) compared to the original roof (between 10:00am and 4:00pm). This is a benefit to the consumer when time-of-use meters are used such as in Ontario; however these meters are not currently used in Hong Kong.

- The surface temperature duration curve show larger temperature fluctuations for the original roof (51˚C) than for the green roof (30˚C), during the month of June. For the green roof this was the case for both predicted and monitored data. The green roof remains at a cooler and more consistent temperature than the original roof. When compared to the cool roof, the cool roof exhibits greater temperature fluctuations than the green roof.

- There is not an appreciable difference in the indoor air temperature fluctuations in the room below the green roof and original roof; however, this results from the use of air conditioning which maintains the temperature fairly constant at 26˚C.

- The indoor air temperature duration curves for the room under the cool roof do not correlate with the surface temperature duration curves. The surface temperature of the cool roof fluctuates more than the green roof's temperature; however, the indoor air temperature of the room under the cool roof is more constant that the indoor air temperature of the room under the green roof. Temperature duration is not the most effective performance measure for indoor air temperature when air conditioning is used, but energy consumption can draw better conclusions.

- From April to September, the cool roof consumes the least amount of energy (in terms of air conditioning usage), although it is more pronounced during the hotter months of June, July, and August. It uses 110 kWh less than the added roof insulation, 184 kWh less than the green roof, 376 kWh less than the reflective windows and 416 kWh less than the original roof.

- In terms of operational cost only, the cool roof is the most cost efficient alternative. From April to September, the cool roof costs $55 less than the green roof, $63 less than the original roof, $57 less than reflective windows, and $17 less than roof insulation.

- The life cycle cost assessment shows that after 20 years the green roof becomes more financially viable than the alternatives (original roof, cool roof, and roof insulation). A full CBA was not performed.

- Overall, using a green roof does reduce heat flux into the building when compared to a traditional roof; however, green roofs are not the only viable option. Cool roofs can provide greater energy savings, especially during the summer months and do not have the added cost of roof irrigation.

6.2 Recommendations

6.2.1 Cost Benefit Analysis

The cost comparison between the green roof, original roof, cool roof, and roof insulation discussed in this thesis only takes into account the cost associated with construction, maintenance, HVAC energy usage, and replacement cost. In order to compare the various alternatives in more detail to draw conclusions on the preferable alternative for wide-scale implementation in Hong Kong, a full CBA should be performed – including all economically relevant factors during installation, building operation, and ongoing maintenance. The assessment in this thesis only included costs and not benefits. In order to calculate the payback period the benefits associated with each option should be quantified in terms of cost. Green roofs have certain benefits that the other options do not have, such as storm water retention, aesthetic appeal, and air quality improvement. Additionally, cool roofs may not be practical in such a highly urbanized city as Hong Kong because of the visual distraction from the reflective coating.

Compared to a typical roof and cool roof, green roofs retain a much higher percentage of storm water. Energy and insulation and air quality are other economically relevant factors that Carter and Keeler (2008) included in their CBA. Peck and Callaghan (1999) also suggested aesthetic appeal, increased property value, and business related cost savings as economically relevant factors.

Once all economically relevant factors are defined, the cost for each should be defined over the defined time horizon. The recommended time horizon is 40 years, as that is the typical lifespan for a green roof (City of Toronto & OCE-ETech, 2005; Carter & Keeler, 2008).

This thesis only analyzed the energy performance for each alternative and found that looking at that factor alone; the green roof was not the most cost effective option. However, performing a CBA will include all economically relevant factors, including social factors, to determine if installing green roofs in Hong Kong is feasible or if another option, such as cool roofs is more practical.

6.2.2 Building Types

Intensive green roofs have gained popularity in Hong Kong, mainly due to their aesthetic benefits; however, extensive green roofs, which are popular in other countries due to their energy savings benefits, are less common in Hong Kong. The feasibility and applicability of installing extensive green roofs, to promote energy savings in Hong Kong, is extremely dependent on the building type. Installing green roofs in the Old City Centre may not be practical because of the very tall and narrow high-rise buildings with very little roof space. Additionally, the energy benefits from green roofs are not as pronounced on high-rise buildings that are 10 to 50 storeys, compared to low-rise buildings. The New City Centre, where the CSMC building is located, has more opportunity for green roof construction because of larger rooftop footprint. Extensive green roofs can be very beneficial to existing lower maintenance buildings because of the lower roof load, limited required maintenance, and energy benefits (Townshend, 2007). The conclusions drawn from this thesis are most applicable to other low-rise buildings in Hong Kong with similar characteristics. In order to draw conclusions regarding wide-scale implementation of extensive green roofs in Hong Kong other studies should be conducted to look at potential energy savings for other building types. Alternatives, such as cool roofs, should also be examined for other building types to see which alternative provides the greatest energy and cost savings.

Appendix A –
EnergyPlus Input File for Green Roof Construction

```
!-Generator IDFEditor 1.37c
!-Option OriginalOrderTop UseSpecialFormat

!-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.

Output:Variable,*,surface outside temperature,Hourly;
Output:Variable,*,Roof Irrigation Scheduled Amount,hourly;
Output:Variable,*,Roof Irrigation Actual Amount,hourly;

Schedule:Compact,
    HTGSETP_SCH,             !- Name
    Temperature,             !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays,           !- Field 2
    Until: 06:00, 13.,       !- Field 4
    Until: 19:00, 21.0,      !- Field 6
    Until: 24:00, 13.,       !- Field 8
    For SummerDesignDay,     !- Field 9
    Until: 24:00, 13.,       !- Field 11
    For: Saturday,           !- Field 12
    Until: 06:00, 13.,       !- Field 14
    Until: 13:00, 21.0,      !- Field 16
    Until: 24:00, 13.,       !- Field 18
    For WinterDesignDay,     !- Field 19
    Until: 24:00, 21.0,      !- Field 21
    For: Sunday Holidays AllOtherDays,  !- Field 22
    Until: 24:00, 13.;       !- Field 24

Schedule:Compact,
    CLGSETP_SCH,             !- Name
    Temperature,             !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays,           !- Field 2
    Until: 06:00, 33.0,      !- Field 4
    Until: 22:00, 26,        !- Field 6
    Until: 24:00, 33.0,      !- Field 8
    For SummerDesignDay,     !- Field 9
    Until: 24:00, 26,        !- Field 11
    For: Saturday,           !- Field 12
    Until: 06:00, 33.0,      !- Field 14
    Until: 18:00, 26,        !- Field 16
    Until: 24:00, 33.0,      !- Field 18
    For WinterDesignDay,     !- Field 19
    Until: 24:00, 33.0,      !- Field 21
    For: Sunday Holidays AllOtherDays,  !- Field 22
    Until: 24:00, 33.0;      !- Field 24

Schedule:Compact,
```

```
    FANANDCOILAVAILSCHED,    !- Name
    FRACTION,                !- Schedule Type Limits Name
    Through: 3/31,           !- Field 1
    For: Alldays,            !- Field 2
    Until: 24:00, 1.00,      !- Field 4
    Through: 9/30,           !- Field 5
    For: Weekdays,           !- Field 6
    Until: 7:00, 0.00,       !- Field 8
    Until: 19:00, 1.00,      !- Field 10
    Until: 24:00, 0.00,      !- Field 12
    For: Weekends Holidays CustomDay1 CustomDay2,  !- Field 13
    Until: 24:00, 0.00,      !- Field 15
    For: SummerDesignDay WinterDesignDay,  !- Field 16
    Until: 24:00, 1.00,      !- Field 18
    Through: 12/31,          !- Field 19
    For: Alldays,            !- Field 20
    Until: 24:00, 1.00;      !- Field 22

Schedule:Compact,
    COOLINGCOILAVAILSCHED,   !- Name
    FRACTION,                !- Schedule Type Limits Name
    Through: 3/31,           !- Field 1
    For: Alldays,            !- Field 2
    Until: 24:00, 0.00,      !- Field 4
    Through: 9/30,           !- Field 5
    For: Weekdays,           !- Field 6
    Until: 7:00, 0.00,       !- Field 8
    Until: 19:00, 1.00,      !- Field 10
    Until: 24:00, 0.00,      !- Field 12
    For: Weekends Holidays CustomDay1 CustomDay2,  !- Field 13
    Until: 24:00, 0.00,      !- Field 15
    For: SummerDesignDay WinterDesignDay,  !- Field 16
    Until: 24:00, 1.00,      !- Field 18
    Through: 12/31,          !- Field 19
    For: Alldays,            !- Field 20
    Until: 24:00, 0.00;      !- Field 22

ScheduleTypeLimits,
    Temperature,             !- Name
    -60,                     !- Lower Limit Value
    200,                     !- Upper Limit Value
    CONTINUOUS,              !- Numeric Type
    Temperature;             !- Unit Type

Output:Variable,*,Window AC Electric Power,hourly;

Material,
    ASHRAE 90.1-2004_Sec 5.5-2_BUILT UP ROOFING 3/8 IN,  !- Name
    VeryRough,               !- Roughness
    0.0095,                  !- Thickness {m}
    0.1600,                  !- Conductivity {W/m-K}
    1121.2900,               !- Density {kg/m3}
    1460.0000,               !- Specific Heat {J/kg-K}
    0.9000,                  !- Thermal Absorptance
```

```
    0.7000,                  !- Solar Absorptance
    0.7000;                  !- Visible Absorptance

Material,
    Roof Insulation_1,       !- Name
    MediumRough,             !- Roughness
    0.0127,                  !- Thickness {m}
    1.436,                   !- Conductivity {W/m-K}
    891,                     !- Density {kg/m3}
    1674,                    !- Specific Heat {J/kg-K}
    0.9000,                  !- Thermal Absorptance
    0.7000,                  !- Solar Absorptance
    0.7000;                  !- Visible Absorptance

Material,
    Roof Bitumen Membrane,   !- Name
    MediumSmooth,            !- Roughness
    0.004,                   !- Thickness {m}
    0.17,                    !- Conductivity {W/m-K}
    1125,                    !- Density {kg/m3}
    1470,                    !- Specific Heat {J/kg-K}
    0.9000,                  !- Thermal Absorptance
    0.7000,                  !- Solar Absorptance
    0.7;                     !- Visible Absorptance

WindowMaterial:Glazing,
    CLEAR 3MM,               !- Name
    SpectralAverage,         !- Optical Data Type
    ,                        !- Window Glass Spectral Data Set Name
    0.003,                   !- Thickness {m}
    0.837,                   !- Solar Transmittance at Normal Incidence
    0.075,                   !- Front Side Solar Reflectance at Normal Incidence
    0.075,                   !- Back Side Solar Reflectance at Normal Incidence
    0.898,                   !- Visible Transmittance at Normal Incidence
    0.081,                   !- Front Side Visible Reflectance at Normal Incidence
    0.081,                   !- Back Side Visible Reflectance at Normal Incidence
    0,                       !- Infrared Transmittance at Normal Incidence
    0.84,                    !- Front Side Infrared Hemispherical Emissivity
    0.84,                    !- Back Side Infrared Hemispherical Emissivity
    0.9;                     !- Conductivity {W/m-K}

FenestrationSurface:Detailed,
    SOUTH WINDOW,            !- Name
    Window,                  !- Surface Type
    DOUBLE PANE WINDOW,      !- Construction Name
    ZONE SURFACE SOUTH,      !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    autocalculate,           !- View Factor to Ground
    ,                        !- Shading Control Name
    ,                        !- Frame and Divider Name
    1,                       !- Multiplier
    4,                       !- Number of Vertices
    2.2, 0, 5.65,                 !- X,Y,Z  1 {m}
    2.2, 0, 4.55,                 !- X,Y,Z  2 {m}
```

```
    8.1, 0, 4.55,                    !- X,Y,Z  3 {m}
    8.1, 0, 5.65;                    !- X,Y,Z  4 {m}

  FenestrationSurface:Detailed,
    EAST WINDOW,             !- Name
    Window,                  !- Surface Type
    DOUBLE PANE WINDOW,      !- Construction Name
    ZONE SURFACE EAST,       !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    autocalculate,           !- View Factor to Ground
    ,                        !- Shading Control Name
    ,                        !- Frame and Divider Name
    1,                       !- Multiplier
    4,                       !- Number of Vertices
    11.81, 7.05, 5.65,               !- X,Y,Z  1 {m}
    11.81, 7.05, 4.55,               !- X,Y,Z  2 {m}
    11.81, 16.1, 4.55,               !- X,Y,Z  3 {m}
    11.81, 16.1, 5.65;               !- X,Y,Z  4 {m}

  FenestrationSurface:Detailed,
    NORTH WINDOW,            !- Name
    Window,                  !- Surface Type
    DOUBLE PANE WINDOW,      !- Construction Name
    SURFACE NORTH,           !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    autocalculate,           !- View Factor to Ground
    ,                        !- Shading Control Name
    ,                        !- Frame and Divider Name
    1,                       !- Multiplier
    4,                       !- Number of Vertices
    3, 18.52, 5.65,                  !- X,Y,Z  1 {m}
    3, 18.52, 4.55,                  !- X,Y,Z  2 {m}
    1.6, 18.52, 4.55,                !- X,Y,Z  3 {m}
    1.6, 18.52, 5.65;                !- X,Y,Z  4 {m}

  FenestrationSurface:Detailed,
    WEST WINDOW,             !- Name
    Window,                  !- Surface Type
    DOUBLE PANE WINDOW,      !- Construction Name
    ZONE SURFACE WEST,       !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    autocalculate,           !- View Factor to Ground
    ,                        !- Shading Control Name
    ,                        !- Frame and Divider Name
    1,                       !- Multiplier
    4,                       !- Number of Vertices
    0, 13.8, 5.65,                   !- X,Y,Z  1 {m}
    0, 13.8, 4.55,                   !- X,Y,Z  2 {m}
    0, 3.3, 4.55,                    !- X,Y,Z  3 {m}
    0, 3.3, 5.65;                    !- X,Y,Z  4 {m}

  Zone,
    ZONE TWO,                !- Name
    0,                       !- Direction of Relative North {deg}
```

```
    0, 0, 0,                          !- X,Y,Z  {m}
    1,                    !- Type
    1,                    !- Multiplier
    autocalculate,          !- Ceiling Height {m}
    autocalculate;          !- Volume {m3}

BuildingSurface:Detailed,
    SURFACE NORTH2,         !- Name
    Wall,                   !- Surface Type
    LTWALL,                 !- Construction Name
    ZONE TWO,               !- Zone Name
    Outdoors,               !- Outside Boundary Condition
    ,                       !- Outside Boundary Condition Object
    SunExposed,             !- Sun Exposure
    WindExposed,            !- Wind Exposure
    0.50,                   !- View Factor to Ground
    4,                      !- Number of Vertices
    11.81, 18.52, 3.5,                !- X,Y,Z  1 {m}
    11.81, 18.52, 0,                  !- X,Y,Z  2 {m}
    0, 18.52, 0,                      !- X,Y,Z  3 {m}
    0, 18.52, 3.5;                    !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
    ZONE SURFACE EAST2,      !- Name
    Wall,                   !- Surface Type
    LTWALL,                 !- Construction Name
    ZONE TWO,               !- Zone Name
    Outdoors,               !- Outside Boundary Condition
    ,                       !- Outside Boundary Condition Object
    SunExposed,             !- Sun Exposure
    WindExposed,            !- Wind Exposure
    0.50,                   !- View Factor to Ground
    4,                      !- Number of Vertices
    11.81, 0, 3.5,                    !- X,Y,Z  1 {m}
    11.81, 0, 0,                      !- X,Y,Z  2 {m}
    11.81, 18.52, 0,                  !- X,Y,Z  3 {m}
    11.81, 18.52, 3.5;                !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
    ZONE SURFACE SOUTH2,     !- Name
    Wall,                   !- Surface Type
    LTWALL,                 !- Construction Name
    ZONE TWO,               !- Zone Name
    Outdoors,               !- Outside Boundary Condition
    ,                       !- Outside Boundary Condition Object
    SunExposed,             !- Sun Exposure
    WindExposed,            !- Wind Exposure
    0.50,                   !- View Factor to Ground
    4,                      !- Number of Vertices
    0, 0, 3.5,                        !- X,Y,Z  1 {m}
    0, 0, 0,                          !- X,Y,Z  2 {m}
    11.81, 0, 0,                      !- X,Y,Z  3 {m}
    11.81, 0, 3.5;                    !- X,Y,Z  4 {m}
```

```
BuildingSurface:Detailed,
   ZONE SURFACE WEST2,      !- Name
   Wall,                    !- Surface Type
   LTWALL,                  !- Construction Name
   ZONE TWO,                !- Zone Name
   Outdoors,                !- Outside Boundary Condition
   ,                        !- Outside Boundary Condition Object
   SunExposed,              !- Sun Exposure
   WindExposed,             !- Wind Exposure
   0.50,                    !- View Factor to Ground
   4,                       !- Number of Vertices
   0, 18.52, 3.5,           !- X,Y,Z  1 {m}
   0, 18.52, 0,             !- X,Y,Z  2 {m}
   0, 0, 0,                 !- X,Y,Z  3 {m}
   0, 0, 3.5;               !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
   ZONE SURFACE FLOOR2,     !- Name
   Floor,                   !- Surface Type
   LTFLOOR,                 !- Construction Name
   ZONE TWO,                !- Zone Name
   Ground,                  !- Outside Boundary Condition
   ,                        !- Outside Boundary Condition Object
   NoSun,                   !- Sun Exposure
   NoWind,                  !- Wind Exposure
   0,                       !- View Factor to Ground
   4,                       !- Number of Vertices
   0, 0, 0,                 !- X,Y,Z  1 {m}
   0, 18.52, 0,             !- X,Y,Z  2 {m}
   11.81, 18.52, 0,         !- X,Y,Z  3 {m}
   11.81, 0, 0;             !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
   ZONE SURFACE CEILING2,   !- Name
   Ceiling,                 !- Surface Type
   LTWALL,                  !- Construction Name
   ZONE TWO,                !- Zone Name
   Surface,                 !- Outside Boundary Condition
   ,                        !- Outside Boundary Condition Object
   NoSun,                   !- Sun Exposure
   NoWind,                  !- Wind Exposure
   0,                       !- View Factor to Ground
   4,                       !- Number of Vertices
   0, 18.52, 3.5,           !- X,Y,Z  1 {m}
   0, 0, 3.5,               !- X,Y,Z  2 {m}
   11.81, 0, 3.5,           !- X,Y,Z  3 {m}
   11.81, 18.52, 3.5;       !- X,Y,Z  4 {m}

NodeList,
   OutsideAirInletNodes,    !- Name
   ZONE1WindACOAInNode;     !- Node 1 Name

NodeList,
   ZONE ONE Supply Inlet,   !- Name
```

```
  ZONE1WindACAirOutletNode;!- Node 1 Name

NodeList,
  ZONE ONE Exhausts,       !- Name
  ZONE1WindACAirInletNode; !- Node 1 Name

SizingPeriod:DesignDay,
  HONG KONG Ann Htg 99.6% Condns DB,  !- Name
  9,                    !- Maximum Dry-Bulb Temperature {C}
  0.0,                  !- Daily Temperature Range {deltaC}
  9,                    !- Humidity Indicating Conditions at Maximum Dry-Bulb
  100547.,              !- Barometric Pressure {Pa}
  4.2,                  !- Wind Speed {m/s}
  30,                   !- Wind Direction {deg}
  0.00,                 !- Sky Clearness
  0,                    !- Rain Indicator
  0,                    !- Snow Indicator
  21,                   !- Day of Month
  1,                    !- Month
  WinterDesignDay,      !- Day Type
  0,                    !- Daylight Saving Time Indicator
  WetBulb;              !- Humidity Indicating Type

SizingPeriod:DesignDay,
  HONG KONG Ann Htg 99% Condns DB,  !- Name
  10.8,                 !- Maximum Dry-Bulb Temperature {C}
  0.0,                  !- Daily Temperature Range {deltaC}
  10.8,                 !- Humidity Indicating Conditions at Maximum Dry-Bulb
  100547.,              !- Barometric Pressure {Pa}
  4.2,                  !- Wind Speed {m/s}
  30,                   !- Wind Direction {deg}
  0.00,                 !- Sky Clearness
  0,                    !- Rain Indicator
  0,                    !- Snow Indicator
  21,                   !- Day of Month
  1,                    !- Month
  WinterDesignDay,      !- Day Type
  0,                    !- Daylight Saving Time Indicator
  WetBulb;              !- Humidity Indicating Type

SizingPeriod:DesignDay,
  HONG KONG Ann Hum_n 99.6% Condns DP=>MCDB,  !- Name
  13.7,                 !- Maximum Dry-Bulb Temperature {C}
  0.0,                  !- Daily Temperature Range {deltaC}
  -3.2,                 !- Humidity Indicating Conditions at Maximum Dry-Bulb
  100547.,              !- Barometric Pressure {Pa}
  4.2,                  !- Wind Speed {m/s}
  30,                   !- Wind Direction {deg}
  0.00,                 !- Sky Clearness
  0,                    !- Rain Indicator
  0,                    !- Snow Indicator
  21,                   !- Day of Month
  1,                    !- Month
  WinterDesignDay,      !- Day Type
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    0,                    !- Daylight Saving Time Indicator
    DewPoint;             !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Hum_n 99% Condns DP=>MCDB,  !- Name
    14.9,                 !- Maximum Dry-Bulb Temperature {C}
    0.0,                  !- Daily Temperature Range {deltaC}
    -0.1,                 !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,              !- Barometric Pressure {Pa}
    4.2,                  !- Wind Speed {m/s}
    30,                   !- Wind Direction {deg}
    0.00,                 !- Sky Clearness
    0,                    !- Rain Indicator
    0,                    !- Snow Indicator
    21,                   !- Day of Month
    1,                    !- Month
    WinterDesignDay,      !- Day Type
    0,                    !- Daylight Saving Time Indicator
    DewPoint;             !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Htg Wind 99.6% Condns WS=>MCDB,  !- Name
    18.1,                 !- Maximum Dry-Bulb Temperature {C}
    0.0,                  !- Daily Temperature Range {deltaC}
    18.1,                 !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,              !- Barometric Pressure {Pa}
    10.5,                 !- Wind Speed {m/s}
    30,                   !- Wind Direction {deg}
    0.00,                 !- Sky Clearness
    0,                    !- Rain Indicator
    0,                    !- Snow Indicator
    21,                   !- Day of Month
    1,                    !- Month
    WinterDesignDay,      !- Day Type
    0,                    !- Daylight Saving Time Indicator
    WetBulb;              !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Htg Wind 99% Condns WS=>MCDB,  !- Name
    17.6,                 !- Maximum Dry-Bulb Temperature {C}
    0.0,                  !- Daily Temperature Range {deltaC}
    17.6,                 !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,              !- Barometric Pressure {Pa}
    9.5,                  !- Wind Speed {m/s}
    30,                   !- Wind Direction {deg}
    0.00,                 !- Sky Clearness
    0,                    !- Rain Indicator
    0,                    !- Snow Indicator
    21,                   !- Day of Month
    1,                    !- Month
    WinterDesignDay,      !- Day Type
    0,                    !- Daylight Saving Time Indicator
    WetBulb;              !- Humidity Indicating Type
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SizingPeriod:DesignDay,
   HONG KONG Ann Clg .4% Condns DB=>MWB,  !- Name
   33.8,                    !- Maximum Dry-Bulb Temperature {C}
   4.7,                     !- Daily Temperature Range {deltaC}
   26.5,                    !- Humidity Indicating Conditions at Maximum Dry-Bulb
   100547.,                 !- Barometric Pressure {Pa}
   5,                       !- Wind Speed {m/s}
   240,                     !- Wind Direction {deg}
   1.00,                    !- Sky Clearness
   0,                       !- Rain Indicator
   0,                       !- Snow Indicator
   21,                      !- Day of Month
   7,                       !- Month
   SummerDesignDay,         !- Day Type
   0,                       !- Daylight Saving Time Indicator
   WetBulb;                 !- Humidity Indicating Type

SizingPeriod:DesignDay,
   HONG KONG Ann Clg 1% Condns DB=>MWB,  !- Name
   33,                      !- Maximum Dry-Bulb Temperature {C}
   4.7,                     !- Daily Temperature Range {deltaC}
   26.3,                    !- Humidity Indicating Conditions at Maximum Dry-Bulb
   100547.,                 !- Barometric Pressure {Pa}
   5,                       !- Wind Speed {m/s}
   240,                     !- Wind Direction {deg}
   1.00,                    !- Sky Clearness
   0,                       !- Rain Indicator
   0,                       !- Snow Indicator
   21,                      !- Day of Month
   7,                       !- Month
   SummerDesignDay,         !- Day Type
   0,                       !- Daylight Saving Time Indicator
   WetBulb;                 !- Humidity Indicating Type

SizingPeriod:DesignDay,
   HONG KONG Ann Clg 2% Condns DB=>MWB,  !- Name
   32.2,                    !- Maximum Dry-Bulb Temperature {C}
   4.7,                     !- Daily Temperature Range {deltaC}
   26.1,                    !- Humidity Indicating Conditions at Maximum Dry-Bulb
   100547.,                 !- Barometric Pressure {Pa}
   5,                       !- Wind Speed {m/s}
   240,                     !- Wind Direction {deg}
   1.00,                    !- Sky Clearness
   0,                       !- Rain Indicator
   0,                       !- Snow Indicator
   21,                      !- Day of Month
   7,                       !- Month
   SummerDesignDay,         !- Day Type
   0,                       !- Daylight Saving Time Indicator
   WetBulb;                 !- Humidity Indicating Type

SizingPeriod:DesignDay,
   HONG KONG Ann Clg .4% Condns WB=>MDB,  !- Name
   30.8,                    !- Maximum Dry-Bulb Temperature {C}
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    4.7,                    !- Daily Temperature Range {deltaC}
    27.7,                   !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,                !- Barometric Pressure {Pa}
    5,                      !- Wind Speed {m/s}
    240,                    !- Wind Direction {deg}
    1.00,                   !- Sky Clearness
    0,                      !- Rain Indicator
    0,                      !- Snow Indicator
    21,                     !- Day of Month
    7,                      !- Month
    SummerDesignDay,        !- Day Type
    0,                      !- Daylight Saving Time Indicator
    WetBulb;                !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Clg 1% Condns WB=>MDB,  !- Name
    30.5,                   !- Maximum Dry-Bulb Temperature {C}
    4.7,                    !- Daily Temperature Range {deltaC}
    27.3,                   !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,                !- Barometric Pressure {Pa}
    5,                      !- Wind Speed {m/s}
    240,                    !- Wind Direction {deg}
    1.00,                   !- Sky Clearness
    0,                      !- Rain Indicator
    0,                      !- Snow Indicator
    21,                     !- Day of Month
    7,                      !- Month
    SummerDesignDay,        !- Day Type
    0,                      !- Daylight Saving Time Indicator
    WetBulb;                !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Clg 2% Condns WB=>MDB,  !- Name
    30.3,                   !- Maximum Dry-Bulb Temperature {C}
    4.7,                    !- Daily Temperature Range {deltaC}
    27,                     !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,                !- Barometric Pressure {Pa}
    5,                      !- Wind Speed {m/s}
    240,                    !- Wind Direction {deg}
    1.00,                   !- Sky Clearness
    0,                      !- Rain Indicator
    0,                      !- Snow Indicator
    21,                     !- Day of Month
    7,                      !- Month
    SummerDesignDay,        !- Day Type
    0,                      !- Daylight Saving Time Indicator
    WetBulb;                !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Clg .4% Condns DP=>MDB,  !- Name
    30,                     !- Maximum Dry-Bulb Temperature {C}
    4.7,                    !- Daily Temperature Range {deltaC}
    26.9,                   !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,                !- Barometric Pressure {Pa}
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    5,                     !- Wind Speed {m/s}
    240,                   !- Wind Direction {deg}
    1.00,                  !- Sky Clearness
    0,                     !- Rain Indicator
    0,                     !- Snow Indicator
    21,                    !- Day of Month
    7,                     !- Month
    SummerDesignDay,       !- Day Type
    0,                     !- Daylight Saving Time Indicator
    DewPoint;              !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Clg 1% Condns DP=>MDB,  !- Name
    29.5,                  !- Maximum Dry-Bulb Temperature {C}
    4.7,                   !- Daily Temperature Range {deltaC}
    26.2,                  !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,               !- Barometric Pressure {Pa}
    5,                     !- Wind Speed {m/s}
    240,                   !- Wind Direction {deg}
    1.00,                  !- Sky Clearness
    0,                     !- Rain Indicator
    0,                     !- Snow Indicator
    21,                    !- Day of Month
    7,                     !- Month
    SummerDesignDay,       !- Day Type
    0,                     !- Daylight Saving Time Indicator
    DewPoint;              !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Clg 2% Condns DP=>MDB,  !- Name
    29.5,                  !- Maximum Dry-Bulb Temperature {C}
    4.7,                   !- Daily Temperature Range {deltaC}
    26.1,                  !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,               !- Barometric Pressure {Pa}
    5,                     !- Wind Speed {m/s}
    240,                   !- Wind Direction {deg}
    1.00,                  !- Sky Clearness
    0,                     !- Rain Indicator
    0,                     !- Snow Indicator
    21,                    !- Day of Month
    7,                     !- Month
    SummerDesignDay,       !- Day Type
    0,                     !- Daylight Saving Time Indicator
    DewPoint;              !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Clg .4% Condns Enth=>MDB,  !- Name
    31.3,                  !- Maximum Dry-Bulb Temperature {C}
    4.7,                   !- Daily Temperature Range {deltaC}
    88.3,                  !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,               !- Barometric Pressure {Pa}
    5,                     !- Wind Speed {m/s}
    240,                   !- Wind Direction {deg}
    1.00,                  !- Sky Clearness
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```
    0,                     !- Rain Indicator
    0,                     !- Snow Indicator
    21,                    !- Day of Month
    7,                     !- Month
    SummerDesignDay,       !- Day Type
    0,                     !- Daylight Saving Time Indicator
    Enthalpy;              !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Clg 1% Condns Enth=>MDB,  !- Name
    31,                    !- Maximum Dry-Bulb Temperature {C}
    4.7,                   !- Daily Temperature Range {deltaC}
    86.7,                  !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,               !- Barometric Pressure {Pa}
    5,                     !- Wind Speed {m/s}
    240,                   !- Wind Direction {deg}
    1.00,                  !- Sky Clearness
    0,                     !- Rain Indicator
    0,                     !- Snow Indicator
    21,                    !- Day of Month
    7,                     !- Month
    SummerDesignDay,       !- Day Type
    0,                     !- Daylight Saving Time Indicator
    Enthalpy;              !- Humidity Indicating Type

  SizingPeriod:DesignDay,
    HONG KONG Ann Clg 2% Condns Enth=>MDB,  !- Name
    30.7,                  !- Maximum Dry-Bulb Temperature {C}
    4.7,                   !- Daily Temperature Range {deltaC}
    85.4,                  !- Humidity Indicating Conditions at Maximum Dry-Bulb
    100547.,               !- Barometric Pressure {Pa}
    5,                     !- Wind Speed {m/s}
    240,                   !- Wind Direction {deg}
    1.00,                  !- Sky Clearness
    0,                     !- Rain Indicator
    0,                     !- Snow Indicator
    21,                    !- Day of Month
    7,                     !- Month
    SummerDesignDay,       !- Day Type
    0,                     !- Daylight Saving Time Indicator
    Enthalpy;              !- Humidity Indicating Type

  Output:Meter,Electricity:HVAC,Monthly;
  Output:Meter,EnergyTransfer:HVAC,Monthly;
  Output:Variable,*,Window AC Total Zone Cooling Rate ,Monthly;

  Material:RoofVegetation,
    Green Roof,            !- Name
    0.2,                   !- Height of Plants {m}
    4.6,                   !- Leaf Area Index {dimensionless}
    0.2,                   !- Leaf Reflectivity {dimensionless}
    0.95,                  !- Leaf Emissivity
    180,                   !- Minimum Stomatal Resistance {s/m}
    GreenRoofSoil,         !- Soil Layer Name
```

```
    MediumSmooth,            !- Roughness
    0.08,                    !- Thickness {m}
    0.4,                     !- Conductivity of Dry Soil {W/m-K}
    766,                     !- Density of Dry Soil {kg/m3}
    1000,                    !- Specific Heat of Dry Soil {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.75,                    !- Visible Absorptance
    0.5,                     !- Saturation Volumetric Moisture Content of the Soil Layer
    0.01,                    !- Residual Volumetric Moisture Content of the Soil Layer
    0.15;                    !- Initial Volumetric Moisture Content of the Soil Layer

  Schedule:Compact,
    IRRIGATIONSCHD,          !- Name
    Any Number,              !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Alldays,            !- Field 2
    Until: 08:00, 0.0,       !- Field 4
    Until: 09:00, .0007,     !- Field 6
    Until: 20:00, 0.0,       !- Field 8
    Until: 21:00, .0007,     !- Field 10
    Until: 24:00, 0;         !- Field 12

  RoofIrrigation,
    SmartSchedule,           !- Irrigation Model Type
    IRRIGATIONSCHD;          !- Irrigation Rate Schedule Name

  Schedule:Compact,
    ALWAYS 120,              !- Name
    Any Number,              !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00, 120;       !- Field 4

  People,
    People,                  !- Name
    ZONE ONE,                !- Zone Name
    ZONE ONE People,         !- Number of People Schedule Name
    People,                  !- Number of People Calculation Method
    40,                      !- Number of People
    ,                        !- People per Zone Floor Area {person/m2}
    ,                        !- Zone Floor Area per Person {m2/person}
    0,                       !- Fraction Radiant
    autocalculate,           !- Sensible Heat Fraction
    ALWAYS 120,              !- Activity Level Schedule Name
    No,                      !- Enable ASHRAE 55 Comfort Warnings
    ZoneAveraged;            !- Mean Radiant Temperature Calculation Type

  Schedule:Compact,
    ZONE ONE People,         !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 12:00, 0,         !- Field 4
```

```
    Until: 15:00, .2,       !- Field 6
    Until: 16:00, .8,       !- Field 8
    Until: 19:00 , 1,       !- Field 10
    Until: 20:00, .8,       !- Field 12
    Until: 21:00, .3,       !- Field 14
    Until: 22:00, .2,       !- Field 16
    Until: 24:00, 0;        !- Field 18

ZoneHVAC:WindowAirConditioner,
    ZONE1WindAC,            !- Name
    COOLINGCOILAVAILSCHED,   !- Availability Schedule Name
    0.6,                    !- Maximum Supply Air Flow Rate {m3/s}
    0.05,                   !- Maximum Outdoor Air Flow Rate {m3/s}
    ZONE1WindACAirInletNode, !- Air Inlet Node Name
    ZONE1WindACAirOutletNode,!- Air Outlet Node Name
    ZONE1WindACOAInNode,     !- Outdoor Air Node Name
    ZONE1WindACExhNode,      !- Air Relief Node Name
    ZONE1WindACOAMixer,      !- Outdoor Air Mixer Name
    ZONE1WindACFan,          !- Fan Name
    ZONE1WindACDXCoil,       !- DX Cooling Coil Name
    CyclingFanSch,           !- Supply Air Fan Operating Mode Schedule Name
    BlowThrough,             !- Fan Placement
    0.001,                   !- Cooling Convergence Tolerance
    Coil:Cooling:DX:SingleSpeed;  !- Cooling Coil Object Type

Schedule:Compact,
    CyclingFanSch,          !- Name
    Fraction,               !- Schedule Type Limits Name
    Through: 12/31,         !- Field 1
    For: AllDays,           !- Field 2
    Until: 24:00, 0;        !- Field 4

OutdoorAir:Mixer,
    ZONE1WindACOAMixer,      !- Name
    ZONE1WindACOAMixerOutletNode,  !- Mixed Air Node Name
    ZONE1WindACOAInNode,     !- Outdoor Air Stream Node Name
    ZONE1WindACExhNode,      !- Relief Air Stream Node Name
    ZONE1WindACAirInletNode; !- Return Air Stream Node Name

Fan:ConstantVolume,
    ZONE1WindACFan,          !- Name
    FANANDCOILAVAILSCHED,    !- Availability Schedule Name
    0.5,                    !- Fan Efficiency
    75,                     !- Pressure Rise {Pa}
    0.6,                    !- Maximum Flow Rate {m3/s}
    0.9,                    !- Motor Efficiency
    1,                      !- Motor In Airstream Fraction
    ZONE1WindACOAMixerOutletNode,  !- Air Inlet Node Name
    ZONE1WindACFanOutletNode,!- Air Outlet Node Name
    General;                !- End-Use Subcategory

Coil:Cooling:DX:SingleSpeed,
    ZONE1WindACDXCoil,       !- Name
    COOLINGCOILAVAILSCHED,   !- Availability Schedule Name
```

```
    10548,                  !- Rated Total Cooling Capacity {W}
    0.75,                   !- Rated Sensible Heat Ratio
    3,                      !- Rated COP
    0.6,                    !- Rated Air Flow Rate {m3/s}
    ,                       !- Rated Evaporator Fan Power Per Volume Flow Rate {W/(m3/s)}
    ZONE1WindACFanOutletNode,!- Air Inlet Node Name
    ZONE1WindACAirOutletNode,!- Air Outlet Node Name
    WindACCoolCapFT,        !- Total Cooling Capacity Function of Temperature Curve Name
    WindACCoolCapFFF,       !- Total Cooling Capacity Function of Flow Fraction Curve Name
    WindACEIRFT,            !- Energy Input Ratio Function of Temperature Curve Name
    WindACEIRFFF,           !- Energy Input Ratio Function of Flow Fraction Curve Name
    WindACPLFFPLR,          !- Part Load Fraction Correlation Curve Name
    ,                       !- Nominal Time for Condensate Removal to Begin {s}
    ,                       !- Ratio of Initial Moisture Evaporation Rate and Steady State Latent Capacity
{dimensionless}
    ,                       !- Maximum Cycling Rate {cycles/hr}
    ,                       !- Latent Capacity Time Constant {s}
    ,                       !- Condenser Air Inlet Node Name
    AirCooled,              !- Condenser Type
    0.9,                    !- Evaporative Condenser Effectiveness {dimensionless}
    ,                       !- Evaporative Condenser Air Flow Rate {m3/s}
    ,                       !- Evaporative Condenser Pump Rated Power Consumption {W}
    ,                       !- Crankcase Heater Capacity {W}
    10;                     !- Maximum Outdoor Dry-Bulb Temperature for Crankcase Heater Operation {C}

Curve:Quadratic,
    WindACCoolCapFFF,       !- Name
    0.8,                    !- Coefficient1 Constant
    0.2,                    !- Coefficient2 x
    0.0,                    !- Coefficient3 x**2
    0.5,                    !- Minimum Value of x
    1.5;                    !- Maximum Value of x

Curve:Quadratic,
    WindACEIRFFF,           !- Name
    1.1552,                 !- Coefficient1 Constant
    -0.1808,                !- Coefficient2 x
    0.0256,                 !- Coefficient3 x**2
    0.5,                    !- Minimum Value of x
    1.5;                    !- Maximum Value of x

Curve:Quadratic,
    WindACPLFFPLR,          !- Name
    0.85,                   !- Coefficient1 Constant
    0.15,                   !- Coefficient2 x
    0.0,                    !- Coefficient3 x**2
    0.0,                    !- Minimum Value of x
    1.0;                    !- Maximum Value of x

Curve:Biquadratic,
    WindACCoolCapFT,        !- Name
    0.942587793,            !- Coefficient1 Constant
    0.009543347,            !- Coefficient2 x
    0.000683770,            !- Coefficient3 x**2
```

```
    -0.011042676,           !- Coefficient4 y
    0.000005249,            !- Coefficient5 y**2
    -0.000009720,           !- Coefficient6 x*y
    12.77778,               !- Minimum Value of x
    23.88889,               !- Maximum Value of x
    23.88889,               !- Minimum Value of y
    46.11111,               !- Maximum Value of y
    ,                       !- Minimum Curve Output
    ,                       !- Maximum Curve Output
    Temperature,            !- Input Unit Type for X
    Temperature,            !- Input Unit Type for Y
    Dimensionless;          !- Output Unit Type

Curve:Biquadratic,
    WindACEIRFT,            !- Name
    0.342414409,            !- Coefficient1 Constant
    0.034885008,            !- Coefficient2 x
    -0.000623700,           !- Coefficient3 x**2
    0.004977216,            !- Coefficient4 y
    0.000437951,            !- Coefficient5 y**2
    -0.000728028,           !- Coefficient6 x*y
    12.77778,               !- Minimum Value of x
    23.88889,               !- Maximum Value of x
    23.88889,               !- Minimum Value of y
    46.11111,               !- Maximum Value of y
    ,                       !- Minimum Curve Output
    ,                       !- Maximum Curve Output
    Temperature,            !- Input Unit Type for X
    Temperature,            !- Input Unit Type for Y
    Dimensionless;          !- Output Unit Type

OutdoorAir:NodeList,
    OutsideAirInletNodes;   !- Node or NodeList Name 1

Sizing:Zone,
    ZONE ONE,               !- Zone Name
    12,                     !- Zone Cooling Design Supply Air Temperature {C}
    50.,                    !- Zone Heating Design Supply Air Temperature {C}
    0.008,                  !- Zone Cooling Design Supply Air Humidity Ratio {kg-H2O/kg-air}
    0.008,                  !- Zone Heating Design Supply Air Humidity Ratio {kg-H2O/kg-air}
    flow/person,            !- Outdoor Air Method
    0.00944,                !- Outdoor Air Flow per Person {m3/s}
    0.0,                    !- Outdoor Air Flow per Zone Floor Area {m3/s-m2}
    0.0,                    !- Outdoor Air Flow per Zone {m3/s}
    0.0,                    !- Zone Sizing Factor
    DesignDay,              !- Cooling Design Air Flow Method
    0,                      !- Cooling Design Air Flow Rate {m3/s}
    ,                       !- Cooling Minimum Air Flow per Zone Floor Area {m3/s-m2}
    ,                       !- Cooling Minimum Air Flow {m3/s}
    ,                       !- Cooling Minimum Air Flow Fraction
    DesignDay,              !- Heating Design Air Flow Method
    0,                      !- Heating Design Air Flow Rate {m3/s}
    ,                       !- Heating Maximum Air Flow per Zone Floor Area {m3/s-m2}
    ,                       !- Heating Maximum Air Flow {m3/s}
```

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    ;                       !- Heating Maximum Air Flow Fraction

Material,
    M08 200mm lightweight concrete block (filled),  !- Name
    MediumRough,             !- Roughness
    0.2032,                  !- Thickness {m}
    0.26,                    !- Conductivity {W/m-K}
    464,                     !- Density {kg/m3}
    880,                     !- Specific Heat {J/kg-K}
    0.9000000,               !- Thermal Absorptance
    0.7000000,               !- Solar Absorptance
    0.7000000;               !- Visible Absorptance

Material,
    M05 20mm concrete block, !- Name
    MediumRough,             !- Roughness
    0.2032,                  !- Thickness {m}
    1.11,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
    920,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    M10 200m concrete block, !- Name
    MediumRough,             !- Roughness
    0.2032,                  !- Thickness {m}
    0.72,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
    920,                     !- Specific Heat {J/kg-K}
    0.9000000,               !- Thermal Absorptance
    0.7000000,               !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    M13 200mm lightweigh concrete,  !- Name
    MediumRough,             !- Roughness
    0.2302,                  !- Thickness {m}
    0.53,                    !- Conductivity {W/m-K}
    1280,                    !- Density {kg/m3}
    840,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    M15 200mm heavyweight concret,  !- Name
    MediumRough,             !- Roughness
    0.2302,                  !- Thickness {m}
    1.95,                    !- Conductivity {W/m-K}
    2240,                    !- Density {kg/m3}
    900,                     !- Specific Heat {J/kg-K}
    0.90,                    !- Thermal Absorptance
```

```
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    G05 25mm wood,           !- Name
    MediumSmooth,            !- Roughness
    0.0254,                  !- Thickness {m}
    0.15,                    !- Conductivity {W/m-K}
    608,                     !- Density {kg/m3}
    1630,                    !- Specific Heat {J/kg-K}
    0.9000,                  !- Thermal Absorptance
    0.7000,                  !- Solar Absorptance
    0.7000;                  !- Visible Absorptance

Material,
    Softwood 25mm,           !- Name
    MediumSmooth,            !- Roughness
    0.025,                   !- Thickness {m}
    0.129,                   !- Conductivity {W/m-K}
    496,                     !- Density {kg/m3}
    1630,                    !- Specific Heat {J/kg-K}
    0.9000,                  !- Thermal Absorptance
    0.7000,                  !- Solar Absorptance
    0.7000;                  !- Visible Absorptance

RunPeriod,
    ,                        !- Name
    1,                       !- Begin Month
    1,                       !- Begin Day of Month
    12,                      !- End Month
    31,                      !- End Day of Month
    UseWeatherFile,          !- Day of Week for Start Day
    Yes,                     !- Use Weather File Holidays and Special Days
    Yes,                     !- Use Weather File Daylight Saving Period
    No,                      !- Apply Weekend Holiday Rule
    Yes,                     !- Use Weather File Rain Indicators
    Yes,                     !- Use Weather File Snow Indicators
    1;                       !- Number of Times Runperiod to be Repeated

Output:Table:SummaryReports,
    AnnualBuildingUtilityPerformanceSummary,  !- Report 1 Name
    InputVerificationandResultsSummary,  !- Report 2 Name
    Climate Summary,         !- Report 3 Name
    EnvelopeSummary;         !- Report 4 Name

OutputControl:Table:Style,
    HTML;                    !- Column Separator

Output:Variable,*,Lights Electric Consumption,Monthly;

Schedule:Compact,
    Office Lighting,         !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
```

```
    For: Weekdays SummerDesignDay,  !- Field 2
    Until: 05:00, 0.05,      !- Field 4
    Until: 07:00, 0.1,       !- Field 6
    Until: 08:00, 0.3,       !- Field 8
    Until: 17:00, 0.9,       !- Field 10
    Until: 18:00, 0.5,       !- Field 12
    Until: 20:00, 0.3,       !- Field 14
    Until: 22:00, 0.2,       !- Field 16
    Until: 23:00, 0.1,       !- Field 18
    Until: 24:00, 0.05,      !- Field 20
    For: Saturday WinterDesignDay,  !- Field 21
    Until: 06:00, 0.05,      !- Field 23
    Until: 08:00, 0.1,       !- Field 25
    Until: 12:00, 0.3,       !- Field 27
    Until: 17:00, 0.15,      !- Field 29
    Until: 24:00, 0.05,      !- Field 31
    For: Sunday Holidays AllOtherDays,  !- Field 32
    Until: 24:00, 0.05;      !- Field 34

ScheduleTypeLimits,
    Fraction,                !- Name
    0.0,                     !- Lower Limit Value
    1.0,                     !- Upper Limit Value
    Continuous;              !- Numeric Type

Lights,
    ZONE ONE Lights,         !- Name
    ZONE ONE,                !- Zone Name
    Office Lighting,         !- Schedule Name
    LightingLevel,           !- Design Level Calculation Method
    1000,                    !- Lighting Level {W}
    ,                        !- Watts per Zone Floor Area {W/m2}
    ,                        !- Watts per Person {W/person}
    0,                       !- Return Air Fraction
    0.72,                    !- Fraction Radiant
    0.18,                    !- Fraction Visible
    1,                       !- Fraction Replaceable
    General,                 !- End-Use Subcategory
    No;                      !- Return Air Fraction Calculated from Plenum Temperature

WindowMaterial:Glazing,
    CLEAR 6MM,               !- Name
    SpectralAverage,         !- Optical Data Type
    ,                        !- Window Glass Spectral Data Set Name
    0.006,                   !- Thickness {m}
    0.775,                   !- Solar Transmittance at Normal Incidence
    0.071,                   !- Front Side Solar Reflectance at Normal Incidence
    0.071,                   !- Back Side Solar Reflectance at Normal Incidence
    0.881,                   !- Visible Transmittance at Normal Incidence
    0.080,                   !- Front Side Visible Reflectance at Normal Incidence
    0.080,                   !- Back Side Visible Reflectance at Normal Incidence
    0.0,                     !- Infrared Transmittance at Normal Incidence
    0.84,                    !- Front Side Infrared Hemispherical Emissivity
    0.84,                    !- Back Side Infrared Hemispherical Emissivity
```

```
    0.9;                     !- Conductivity {W/m-K}

WindowMaterial:Gas,
    AIR 3MM,                 !- Name
    Air,                     !- Gas Type
    0.0032;                  !- Thickness {m}

Construction,
    DOUBLE PANE WINDOW,      !- Name
    CLEAR 3MM,               !- Outside Layer
    AIR 3MM,                 !- Layer 2
    CLEAR 3MM;               !- Layer 3

Output:Surfaces:List,Details;
! Introduction to EnergyPlus - Exercise 1D
!
! Building: Fictional 1 zone building with lightweight walls and 2 windows.
!          8m x 6m x 2.7m high, long side facing N and S
!          Windows on east and west walls
!          20C heating, 24C cooling
! Internal: Lights, 1000W, Office Lighting schedule, surface-mounted flurorescent
! System:   Purchased Air.
! Plant:    None.
! Environment:  Annual weather file
!
!
Version,5.0;

Building,
    Kindergarten,            !- Name
    0.0,                     !- North Axis {deg}
    City,                    !- Terrain
    0.04,                    !- Loads Convergence Tolerance Value
    0.4,                     !- Temperature Convergence Tolerance Value {deltaC}
    FullInteriorAndExterior, !- Solar Distribution
    ;                        !- Maximum Number of Warmup Days

Timestep,4;
SurfaceConvectionAlgorithm:Inside,Detailed;
SurfaceConvectionAlgorithm:Outside,Detailed;
HeatBalanceAlgorithm,ConductionTransferFunction;

ShadowCalculation,
    20;                      !- Calculation Frequency

SimulationControl,
    Yes,                     !- Do Zone Sizing Calculation
    No,                      !- Do System Sizing Calculation
    No,                      !- Do Plant Sizing Calculation
    No,                      !- Run Simulation for Sizing Periods
    Yes;                     !- Run Simulation for Weather File Run Periods

Site:Location,
    Hong Kong_SAR_CHN,       !- Name
```

```
    22.32,                  !- Latitude {deg}
    114.17,                 !- Longitude {deg}
    8,                      !- Time Zone {hr}
    65;                     !- Elevation {m}

Site:GroundTemperature:BuildingSurface,20,20,20,20,20,20,20,20,20,20,20,20;

Material,
    PLASTERBOARD-1,         !- Name
    MediumSmooth,           !- Roughness
    0.01200,                !- Thickness {m}
    0.16000,                !- Conductivity {W/m-K}
    950.000,                !- Density {kg/m3}
    840.00,                 !- Specific Heat {J/kg-K}
    0.900000,               !- Thermal Absorptance
    0.600000,               !- Solar Absorptance
    0.600000;               !- Visible Absorptance

Material,
    FIBERGLASS QUILT-1,     !- Name
    Rough,                  !- Roughness
    0.066,                  !- Thickness {m}
    0.040,                  !- Conductivity {W/m-K}
    12.000,                 !- Density {kg/m3}
    840.00,                 !- Specific Heat {J/kg-K}
    0.900000,               !- Thermal Absorptance
    0.600000,               !- Solar Absorptance
    0.600000;               !- Visible Absorptance

Material,
    WOOD SIDING-1,          !- Name
    Rough,                  !- Roughness
    0.00900,                !- Thickness {m}
    0.14000,                !- Conductivity {W/m-K}
    530.000,                !- Density {kg/m3}
    900.00,                 !- Specific Heat {J/kg-K}
    0.900000,               !- Thermal Absorptance
    0.600000,               !- Solar Absorptance
    0.600000;               !- Visible Absorptance

Material,
    PLASTERBOARD-2,         !- Name
    Rough,                  !- Roughness
    0.01000,                !- Thickness {m}
    0.16000,                !- Conductivity {W/m-K}
    950.000,                !- Density {kg/m3}
    840.00,                 !- Specific Heat {J/kg-K}
    0.900000,               !- Thermal Absorptance
    0.600000,               !- Solar Absorptance
    0.600000;               !- Visible Absorptance

Material,
    FIBERGLASS QUILT-2,     !- Name
    Rough,                  !- Roughness
```

```
    0.1118,                 !- Thickness {m}
    0.040,                 !- Conductivity {W/m-K}
    12.000,                 !- Density {kg/m3}
    840.00,                 !- Specific Heat {J/kg-K}
    0.900000,               !- Thermal Absorptance
    0.600000,               !- Solar Absorptance
    0.600000;               !- Visible Absorptance

Material,
    ROOF DECK,              !- Name
    Rough,                  !- Roughness
    0.01900,                !- Thickness {m}
    0.14000,                !- Conductivity {W/m-K}
    530.000,                !- Density {kg/m3}
    900.00,                 !- Specific Heat {J/kg-K}
    0.900000,               !- Thermal Absorptance
    0.600000,               !- Solar Absorptance
    0.600000;               !- Visible Absorptance

Material,
    HF-C5,                  !- Name
    MediumRough,            !- Roughness
    0.1015000,              !- Thickness {m}
    1.729600,               !- Conductivity {W/m-K}
    2243.000,               !- Density {kg/m3}
    837.0000,               !- Specific Heat {J/kg-K}
    0.9000000,              !- Thermal Absorptance
    0.6500000,              !- Solar Absorptance
    0.6500000;              !- Visible Absorptance

Construction,
    LTWALL,                 !- Name
    M08 200mm lightweight concrete block (filled);  !- Outside Layer

Construction,
    LTFLOOR,                !- Name
    M08 200mm lightweight concrete block (filled);  !- Outside Layer

Construction,
    LTROOF,                 !- Name
    Green Roof,             !- Outside Layer
    M08 200mm lightweight concrete block (filled);  !- Layer 2

Zone,
    ZONE ONE,               !- Name
    0,                      !- Direction of Relative North {deg}
    0, 0, 0,                !- X,Y,Z  {m}
    1,                      !- Type
    1,                      !- Multiplier
    autocalculate,          !- Ceiling Height {m}
    autocalculate;          !- Volume {m3}

GlobalGeometryRules,
    UpperLeftCorner,        !- Starting Vertex Position
```

```
    Counterclockwise,        !- Vertex Entry Direction
    WorldCoordinateSystem;   !- Coordinate System

BuildingSurface:Detailed,
    SURFACE NORTH,           !- Name
    Wall,                    !- Surface Type
    LTWALL,                  !- Construction Name
    ZONE ONE,                !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.50,                    !- View Factor to Ground
    4,                       !- Number of Vertices
    11.81, 18.52, 7,                   !- X,Y,Z  1 {m}
    11.81, 18.52, 3.5,                 !- X,Y,Z  2 {m}
    0, 18.52, 3.5,                     !- X,Y,Z  3 {m}
    0, 18.52, 7;                       !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
    ZONE SURFACE EAST,       !- Name
    Wall,                    !- Surface Type
    LTWALL,                  !- Construction Name
    ZONE ONE,                !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.50,                    !- View Factor to Ground
    4,                       !- Number of Vertices
    11.81, 0, 7,                       !- X,Y,Z  1 {m}
    11.81, 0, 3.5,                     !- X,Y,Z  2 {m}
    11.81, 18.52, 3.5,                 !- X,Y,Z  3 {m}
    11.81, 18.52, 7;                   !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
    ZONE SURFACE SOUTH,      !- Name
    Wall,                    !- Surface Type
    LTWALL,                  !- Construction Name
    ZONE ONE,                !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.50,                    !- View Factor to Ground
    4,                       !- Number of Vertices
    0, 0, 7,                           !- X,Y,Z  1 {m}
    0, 0, 3.5,                         !- X,Y,Z  2 {m}
    11.81, 0, 3.5,                     !- X,Y,Z  3 {m}
    11.81, 0, 7;                       !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
    ZONE SURFACE WEST,       !- Name
    Wall,                    !- Surface Type
```

```
    LTWALL,                  !- Construction Name
    ZONE ONE,                !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.50,                    !- View Factor to Ground
    4,                       !- Number of Vertices
    0, 18.52, 7,                        !- X,Y,Z  1 {m}
    0, 18.52, 3.5,                      !- X,Y,Z  2 {m}
    0, 0, 3.5,                          !- X,Y,Z  3 {m}
    0, 0, 7;                            !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
    ZONE SURFACE FLOOR,      !- Name
    Floor,                   !- Surface Type
    LTFLOOR,                 !- Construction Name
    ZONE ONE,                !- Zone Name
    Ground,                  !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    0,                       !- View Factor to Ground
    4,                       !- Number of Vertices
    0, 0, 3.5,                          !- X,Y,Z  1 {m}
    0, 18.52, 3.5,                      !- X,Y,Z  2 {m}
    11.81, 18.52, 3.5,                  !- X,Y,Z  3 {m}
    11.81, 0, 3.5;                      !- X,Y,Z  4 {m}

BuildingSurface:Detailed,
    ZONE SURFACE ROOF,       !- Name
    Roof,                    !- Surface Type
    LTROOF,                  !- Construction Name
    ZONE ONE,                !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0,                       !- View Factor to Ground
    4,                       !- Number of Vertices
    0, 18.52, 7,                        !- X,Y,Z  1 {m}
    0, 0, 7,                            !- X,Y,Z  2 {m}
    11.81, 0, 7,                        !- X,Y,Z  3 {m}
    11.81, 18.52, 7;                    !- X,Y,Z  4 {m}

ScheduleTypeLimits,
    Any Number;              !- Name

Schedule:Compact,
    ALWAYS 4,                !- Name
    Any Number,              !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00, 4;         !- Field 4
```

```
Schedule:Compact,
   ALWAYS 20,              !- Name
   Any Number,             !- Schedule Type Limits Name
   Through: 12/31,         !- Field 1
   For: AllDays,           !- Field 2
   Until: 24:00, 20;       !- Field 4

Schedule:Compact,
   ALWAYS 24,              !- Name
   Any Number,             !- Schedule Type Limits Name
   Through: 12/31,         !- Field 1
   For: AllDays,           !- Field 2
   Until: 24:00, 24;       !- Field 4

ZoneHVAC:EquipmentConnections,
   ZONE ONE,               !- Zone Name
   ZONE ONE Equipment,      !- Zone Conditioning Equipment List Name
   ZONE ONE Supply Inlet,   !- Zone Air Inlet Node or NodeList Name
   ZONE ONE Exhausts,       !- Zone Air Exhaust Node or NodeList Name
   ZONE ONE Zone Air Node,  !- Zone Air Node Name
   ZONE ONE Return Outlet;  !- Zone Return Air Node Name

ZoneHVAC:EquipmentList,
   ZONE ONE Equipment,      !- Name
   ZoneHVAC:WindowAirConditioner,  !- Zone Equipment 1 Object Type
   ZONE1WindAC,            !- Zone Equipment 1 Name
   1,                      !- Zone Equipment 1 Cooling Sequence
   2;                      !- Zone Equipment 1 Heating or No-Load Sequence

ZoneControl:Thermostat,
   ZONE ONE Thermostat,     !- Name
   ZONE ONE,               !- Zone Name
   ALWAYS 4,               !- Control Type Schedule Name
   ThermostatSetpoint:DualSetpoint,  !- Control 1 Object Type
   Office Thermostat Dual SP Control;  !- Control 1 Name

ThermostatSetpoint:DualSetpoint,
   Office Thermostat Dual SP Control,  !- Name
   HTGSETP_SCH,            !- Heating Setpoint Temperature Schedule Name
   CLGSETP_SCH;            !- Cooling Setpoint Temperature Schedule Name

Output:Variable,*,Outdoor Dry Bulb,Monthly;
Output:Variable,*,Zone/Sys Sensible Cooling Energy,Monthly;
Output:Variable,*,Zone/Sys Sensible Heating Energy,Monthly;
Output:Variable,*,Zone/Sys Air Temperature,Hourly;
Output:Surfaces:Drawing,DXF;
Output:Constructions,Constructions;
Output:VariableDictionary,Regular;
```

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