Development of a Modeling Software Tool to Optimize Energy Performance of Medium-Size Office Buildings at the Early Design Stage

by:

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Building energy modeling is an important tool for low-energy building design. An energy modeling tool is used to estimate energy consumption, peak heating and cooling load for sizing mechanical equipment, and to demonstrate compliance with building codes and standards. Modeling tools are designed to evaluate building performance associated with a set of building specifications but it is difficult to predict building loads at the early design stage because most design features have not yet been specified. In addition, the designer must have experience and insight regarding the design features that most strongly influence building performance.

In this thesis, a new modeling tool, entitled Excel-Based Load Model (EBLM), was developed to aid designers in the early design stage to estimate building loads, and to size/specify the building components that most strongly affect the overall building performance. EBLM is an open source tool that uses Excel as the calculation engine, creating the advantage that users may modify the program according to their individual interests or project needs.

EBLM is a single zone modeling tool that consists of three parts: inputs, load calculations, and outputs. The load calculations use the conduction time series (CTS) and radiant time series (RTS) methods to account for the thermal storage effect that delays cooling load.

One of the unique features of EBLM is the ability to model slat-type operable shading systems. Users can specify one of three shading control strategies. Results can be

presented in hourly, monthly, or annual format. The program also outputs the percentage of building loads for each building component in figures and tables.

The EBLM has been validated with the commonly used eQUEST model; the difference is about 8% for the sum of all building loads.

EBLM was also used to perform a series of simulations to examine the influence of building components that are considered to be important. The major conclusions were:

- High performance building specifications significantly reduce building loads, and energy-efficient mechanical equipment could further reduce energy consumption.
- An outdoor operable shading system can be used to effectively block excess solar gain and to help reduce cooling load in summer months, but can also be operated to allow solar gain and to reduce heating load in winter months.
- Using an outdoor temperature shading control strategy, low solar heat gain coefficient (SHGC) windows with an outdoor operable shading system have better energy performance than high SHGC windows with outdoor operable shading system in Toronto.
- As found in many studies, the window-to-wall ratio (WWR) has a significant influence on building performance. Lower WWR can minimize both the conductive heat transfer and alleviate excess solar gain.
- Lowering the WWR from 40% to 30% has a similar effect on energy use as deploying outdoor operable shading system.

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Table of Contents

List of Figures

List of Tables

Nomenclature

A = surface area, m^2

ACH = number of air changes per hour, hr^{-1} in service

A_{cg} = area of the center glass, m^2

A_{eg} = area of the edge glass, m^2

A_{floor} = floor area, m^2

A_{fr} = area of the frame, m^2

A_{tot} = total window area, including center glass, edge glass, and frame, m$_2$

A_{view} = view area of windows, m^2

c_0, c_0, etc = conduction time factor

C_p = specific heat of the air, J/(kg-C)

C_T = a constant, 3600

e_n = eccentricity factor

EOT = equation of time

E_t = total solar radiation incident on surface, W/(m^{2}K)

F_r = fraction radiant

$G_{O,H}$ = instantaneous extraterrestrial irradiation on the horizontal surface, W/m^2

$G_{S,C}$ = solar constant 1367 W/m^2

$G_{b,H}$ = instantaneous direct-beam radiation on the horizontal surface, W/m^2

$G_{b,t}$ = direct-beam radiation on the tilted (normal) surface, W/m^2

$G_{d,H}$ = instantaneous diffuse radiation on the horizontal surface, W/m^2

$G_{d,v}$ = diffuse radiation on the vertical surface, W/m^2

G_d = sum of the diffuse and reflected solar radiation, W/m^2

$G_{g,t}$ = reflected radiation on the tilted (normal) surface, W/m^2

$G_{t,H}$ = solar flux on horizontal surface, W/m^2

h_0 = surface film coefficient, 17 W/(m^{2}K)

$IAC\ (\theta, \grave{}\Omega)$ = fraction of heat flow that enters the room, some energy having been excluded by the shading, and is function of incident angle and profile angle

IAC_0 = fraction of heat flow (direct beam) that enters the room by shading at profile angle of 0 degree

IAC_{60} = fraction of heat flow (direct beam) that enters the room by shading at profile angle of 60 degree

IAC_{diff} = fraction of heat flow (diffuse and reflected) that enters the room by shading

$I_{O,H}$ = hourly extraterrestrial irradiation on the horizontal surface, W/m^2

$I_{b,H}$ = hourly direct-beam radiation on the horizontal surface, W/m^2

$I_{d,H}$= hourly diffuse radiation on the horizontal surface, W/m^2

$I_{t,H}$= hourly solar flux on horizontal surface, W/m^2

k = hourly diffuse radiation clearness index

k_t= hourly total radiation clearness index

LCT = local civil time determined at the longitude of the observer

L_{LOC} = local meridian, degree

LPD = lighting power density, W/m^2

L_{ST} = standard meridian, degree

n =Julian day

n_p = number of people

PD = plug load power density, W/m^2

$q_{al,s}$ = required sensible load for air leakage, W

q_r = hourly heat gain accounting for delay effect (RTS), W

$q_{i,r}$ = heat input for current hour (RTS), W

q_{r-23} = heat input 23 hours ago (RTS), W

q_θ = hourly conductive heat gain for surface (CTS), W

$q_{\theta-23}$ = heat input 23 hours ago (CTS), W

$q_{i,\theta}$ = heat input for current hour (CTS), hr

$q_{i,\theta-n}$= conductive heat gain caused by $t_{e,\theta-n}$, W

$q_{lighting}$ = heat generated by lighting, W

q_{loss} = heat transfer through the building enclosure, W

$q_{plug\ load}$ = heat generated by plug load, W

q_s = required sensible load for ventilation, W

$q_{win,ar,delayed}$ = delayed cooling load from windows, W

$q_{win,ar,immediate}$ = immediate cooling load from windows, W

$q_{win,ar}$ = absorbed/redirected solar gain from windows, W

$q_{win,c,delayed}$ = delayed cooling load for windows, W

$q_{win,c,immediate}$ = immediate cooling load for windows, W

$q_{win,c}$ = conductive heat transfer through windows, W

$q_{win,d}$ = direct transmission heat gain through windows, W

Q_{al} = infiltration rate, m^3/s

Q_v = required ventilation rate, L/s

r_0, r_1, etc = radiant time factor

R = R-value of the building enclosure, $m^{20}C/W$

R_a = outdoor air rate per unit area, L/s-m^2

R_f = radiant fraction, ratio of radiative heat transfer to total heat transfer, on room side of glazing system

R_p = people outdoor air rate. L/s-person

δ = declination angle

$SHGC\ (\theta)$ = solar heat gain coefficient of the window at arbitrary incident angle

$SHGC_{cg}$ = the solar heat gain coefficient of the center-glass

$SHGC_{eg}$ = the solar heat gain coefficient of the edge-glass

$SHGC_{fr}$ = the solar heat gain coefficient of the window frame

$SHGC_{product}$ = solar heat gain coefficient of the window product

$SHGC_{shaded,b}$= shaded solar heat gain coefficient of direct bean radiation

$SHGC_{shaded,d,r}$ = shaded solar heat gain coefficient of diffuse and reflected radiation

ST = Standard Time

t = the number of hours before or after solar noon, - before noon, + after noon

$T_{e,\theta-n}$= sol-air temperature n hours ago

T_e= sol-air temperature, ^{0}C

T_{in} = indoor temperature of the building, ^{0}C

T_{out} = outdoor temperature, ^{0}C

T_{rc} = presumed constant room air temperature, ^{0}C

U = overall hear transfer coefficient for surface, W/(m^2K)

U_{Win} = total window U-value, W/m^{20}C

V = gross space volume, m^3

V_O = specific volume, m^3/kg

w = hour angle

ws = wind speed, km/h

WSF = wind speed factor

α_s = the solar altitude angle, degree

γ_s= solar azimuth angle

θ_z = the solar zenith angle, degree

ρ_g = ground reflectance

τ_{cg} = solar transmittance of the center glass

$\tau_{shaded,b}$ = shaded solar transmittance for beam radiation

$\tau_{shaded,d,r}$ = shaded solar transmittance for diffuse and reflected radiation

τ_{sol} = solar transmittance of the window product

$\emptyset$ = latitude

`Ω = profile angle

α = absorptance of surface for solar radiation

β = a surface tilt from horizontal, and usually used for elevation angle, degree

γ = surface azimuth from south, degree

$\varepsilon\Delta R$ = 0 for vertical surfaces

$\varepsilon\Delta R$ = 4 K for horizontal surfaces

θ = incident angle

$\tau(\theta)$ = the solar transmittance of the window at arbitrary incident angle

Abbreviations

ACH – Air Change per Hour

AEDG – Advanced Energy Design Guide

AGSL – Advanced Glazing System Laboratory

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

ASTM – American Society for Testing and Materials

bEQ – Building Energy Quotient

CAV – Constant Air Volume

CFC – Complex Fenestration Construction

CFL – Compact Fluorescent Lamp

CTS – Conduction Time Series

DOAS – Dedicated Outdoor Air System

DOE – US Department of Energy

EBLM – Excel-Based Load Model

EOT – Equation of Time

GDP – Gross Domestic Product

HVAC – Heating, Ventilation and Air-Conditioning

IAC – Indoor Solar Attenuation Coefficient

IGU – Insulated Glazing Unit

LCT – Local Civil Time

LED – Light Emitting Diode

LEED – Leadership in Energy & Environmental Design

LST – Local Solar Time

MNECB – Model National Energy Code of Canada for Buildings

NBCC – National Building Code of Canada

NRC – Natural Research Council of Canada

NRCan – Natural Resources Canada

RTS – Radiant Time Series

SHGC – Solar Heat Gain Coefficient

VAV – Variable Air Volume

WWR – Window-to-Wall Ratio

1.0 Introduction

The total energy consumption of commercial and institutional buildings accounts for 12% of Canada's secondary energy use (NRCan 2013). The sense of saving building energy consumption has raised in recent decades. In addition, greenhouse gas emission becomes a major concern while designing new buildings. Therefore, in order to reduce energy consumption and gas emissions of buildings, the idea of low energy consumption building is a goal that architects and engineers are trying to achieve for every building project. Success in this regard requires designers to have well-established building construction standards, appropriate building design tools including hardware and software, and excellent knowledge of building science.

In practice, as a building project is created, an owner management team establishes a list of requirements and hires a team of architects to define building layouts, enclosures and interior spaces, and cooperate with sub-consultants such as civil, mechanical, and electrical engineers to design the plumbing, mechanical and lighting systems. A poor architectural design may impose heavy building loads and increase the mechanical load, and a poor mechanical design may result in an over-sized mechanical system and waste the initial savings from a good architectural design.

In general building construction, existing standards such as the Model National Energy Code of Canada (MNECB) and ASHRAE 90.1 (2013) establish limits to building elements including window-to-wall ratio (WWR), minimum insulation levels of the building envelope, maximum infiltration and exfiltration, minimum lighting and equipment efficiency, comfort levels (ASHRAE 55-2004), and mechanical systems. Existing standards only provide minimum guidelines of building construction for code compliance. These minimum standards are not intended to encourage designers to achieve higher building performance.

The focus of energy-efficient building design is gradually changed to small and medium-sized commercial buildings. Small and medium-sized businesses (non-agricultural business sector) with less than 500 employees make a significant contribution to the gross domestic product (GDP) of Canada. According to recent economic research in the entire non-agricultural business sector, small and medium-sized businesses with fewer than 500 employees account for 54% of GDP in Canada and 51% of GDP in the United States (Leung & Rispoli 2011). In addition, a more recent report indicates that global market investment in building energy management systems (BEMSs) for small and medium-sized buildings is expected to total nearly $6.1 billion from 2014 to 2022 (Navigant Research 2014).

1.1 Need for Building Modeling Tool at the Early Design Stage

Many researchers have observed that modeling is important to explore design parameters that strongly influence building performance at the early design stage (Urban 2007, Hanam 2010, Attia 2011, Garg 2014, and Maassen 2003). For example, Urban (2007) wrote that: "*Early-stage simulation must allow the user to explore many options quickly. Most building simulation programs have been structured for modeling finalized building designs very accurately. Intricate detail, often including CAD models, must be entered before such simulations can take place. This can take hours or days to prepare, which is not useful for early-stage design iteration. Further, most simulation tools require a technical background and substantial user training before they may be used effectively.*

By simplifying the modeling process, and specifically the user-interface, it is possible to make simulation tools accessible to a wider audience".

The early design stage modeling tool developed in thesis is easier and simpler than other building modeling programs, asking only for the information that would be known at the early design stage, and focuses on the key factors that impact building performance.

As shown in the literature review of this thesis, the U-value of windows, Solar Heat Gain Coefficient (SHGC), Window-to-Wall Ratio (WWR), operable shading control strategy, R-value of walls and roof, ventilation rate, air leakage, occupancy, lighting density and plug loads are widely known to be important design parameters, and therefore are included in the early design stage modeling tool developed here.

1.2 Objectives

This thesis has several objectives. They are to:

1. Primarily, create an easy-to-use and simple building modeling tool – the Excel-Based Load Model (EBLM) that allows users (mechanical engineers and architects) to estimate building loads at the early design stage.
2. Provide a comparison of EBLM simulations to explore the technology of high performance buildings.
3. Use EBLM to demonstrate the energy benefits of an operable shading system.
4. Use EBLM to illustrate the effects of different WWR on building loads.

1.3 Scope

This thesis documents the process of creating the EBLM to estimate building loads (not mechanical system loads) at the early design stage. The tool focuses on estimation of building loads, rather than energy consumption by building mechanical systems, as the mechanical system design is rarely, if ever, known at the early design stage. The primary decisions that EBLM is intended to support are the building shape and orientation (size is usually fixed by the architectural requirements) and the specifications of the building enclosure (including windows and areas) and lighting systems for the intended occupancy of the proposed building.

The present work on EBLM is restricted to the analysis of medium-sized commercial (office) buildings.

- As a result of the restriction to medium-sized building, in the present work, each floor is considered to be a single zone (i.e., the perimeter/core zone effect is not considered).
- Stack effect and elevator energy use are not built into the EBLM calculation engine; and the heat loss through the basement is not calculated because it is assumed to contribute only a small portion of total building load for commercial buildings.

1.4 Approach

The EBLM is an easy-to-use, and simple building modeling tool that integrates basic building design parameters to aid designers in making major decisions at the early design stage. EBLM uses Excel as a calculation engine. In addition, designers can modify the program because the code is effectively open source. For instance, models could easily be added to deal with a core zone, stack effect and/or basement heat loss.

Chapter 2 provides background and literature review on previous research on high performance buildings as well as major factors (e.g., building modeling tool, U-value of windows, WWR, SHGC, building enclosure) affecting building load.

Chapter 3 describes the process of developing EBLM, which includes the basic inputs required, and equations that are used to calculate the building load in the load calculation model.

Chapter 4 compares results of EBLM with those of eQUEST, including monthly solar gain and conductive gains through windows, conductive heat transfer through walls and roof, lighting, plug loads, occupants, and air leakage as well as annual building load.

Chapter 5 presents various building simulations to demonstrate the importance of building specifications, the benefit of outdoor operable shading, and the influence of WWRs on building performance.

Chapter 6 provides conclusions and recommendations for improvements to both EBLM and building designs.

2.0 Background and Literature Review

One definition for a high performance building is provided by the US Energy Policy Act of 2005 Section 914 Building Standards: “High performance building means a building that integrates and optimizes all major high-performance building attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity.” (U.S Congress 2005)

The need for high performance buildings is increasing rapidly as people begin to realize the cost of energy and the benefits of productivity (ASHRAE 2011). Hundreds of research projects have been completed on minimizing building loads and greenhouse emissions (ASHRAE 2014). Researchers have developed ways to educate building owners and designers through technical papers, magazines, energy modeling tools, and seminars.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) regularly publishes standards, design handbooks and seminars to guide designers (ASHRAE 2014). Many professional building consultants also develop their own official training websites, including consultation, information about on-going projects, bookstores, and seminars (Building Science Corporation 2014). People can now easily access various sources to obtain the knowledge and skills needed to design high-performance buildings.

A high-performance building should have a very good building enclosure and very good mechanical systems and controls. Even with less than highly efficient mechanical systems, a well-designed building enclosure can produce an acceptable building (Straube

2014). However, a dysfunctional HVAC or enclosure system will make it essentially impossible to achieve high-performance building.

Designing a good building is a complex job that requires excellent cooperation between architects and engineers. A wrong decision at the early design stage may lead to serious consequences. For instance, in a cold climate, a decision of choosing a glazing panel with low solar heat gain coefficient (SHGC) can reduce the solar heat gain but increase the required heating load: the correct choice of the glazing system depends on orientation, building shape, and window area. Therefore, knowing the major factors that affect the building performance is critical for designers before they make any design decisions. In this section, previous research is reviewed, and factors affecting building performance are documented, allowing readers to better understand the influence of building components on building performance.

2.1 Role of Building Simulation

With the increasing demand for improved energy performance, building energy modeling software is being used more extensively for design decision support. Many building energy modelling programs have been developed. The United States Department of Energy (DOE) provides a directory of information on 417 software tools for evaluating energy efficiency, renewable energy, and sustainability in buildings (DOE 07 01, 2014).

It is difficult to design a building energy model that has the capability of calculating accurate building energy performance because of assumptions that must be made and evaluated through the modeling process. Most energy modeling programs are complicated and require many assumptions at the early design stage. This creates a steep learning curve for designers. For example, architects often ask what type of window system should be entered into the modeling program to get the best performance for the south wall. Sometimes, defining this level of detail is quite difficult at the early design stage.

The process of creating an energy model means more than simply constructing a building in a software program. There are four reasons for using a building energy model: demonstrating code compliance, estimating design performance, comparing to known performance and verification data, and developing building asset ratings (Higgins 2012). Early design stage modeling tools are intended to estimate building performance based on design parameters that would be known as important, whereas commonly used software such as eQUEST is usually used near the end of the design cycle to demonstrate compliance with codes or standards.

2.1.1 Code Compliance

One of the key features of building modeling programs is to compare the calculated energy consumption of a building design to the reference baseline building in order to demonstrate that the design complies with the minimum performance provided by a government standard or other codes. This step is typically performed at the end of the design phase. Sometimes, it may be performed earlier in the design stage to determine if there is a need to make a design change to comply with the code (Higgins 2012).

2.1.2 Estimating Design Performance

It is not a difficult job to meet the minimum performance requirements in building design, but is generally a challenge to outperform code compliance or standard practice. Modeling is performed through the design phase with a variety of parameter inputs, making sure that the building energy performance exceeds the minimum standard (e.g., achieve LEED certification). Designers typically create multiple alternatives with different building systems and components to compare, and to decide on the alternative that has the best performance or to arrive at the best compromise between performance and cost.

2.1.3 Measurement and Verification

After a building is constructed and occupied, the performance can be measured, most easily from utility data. Results generated from the associated building model can be verified with the measured data. The building model can be tuned by adjusting various inputs to match the actual building operating conditions. If the model output closely matches measured data, the model can be used as a reference for different operations and climate, etc. to estimate future performance and savings (Higgins 2012).

2.1.4 Developing Building Asset Ratings

There is a new and growing field to model commercial buildings to develop asset ratings, supported by the ASHRAE Building Energy Quotient (bEQ) program. The benefits of bEQ are as follows:

- Determine potential energy efficiency of the building with an As-Designed evaluation
- Improve performance and energy efficiency with an In-Operation assessment
- Use bEQ to make informed decisions for managing the real estate portfolio

2.2 Fenestration Systems

Highly-glazed buildings have become more popular as they are perceived to provide better daylighting and exterior views, and some consider them aesthetically pleasing. Designers often miscalculate the Window-to-Wall Ratio (WWR) balance point between solar gain and conductive heat transfer through the building enclosure. For example having a large WWR increases the solar gain and offsets heating load during cold days, but large WWR will lower the overall insulation level of the building enclosure and increases heat loss during cold nights. For a building enclosure with a small WWR, the building energy performance is more closely connected to the thermal properties of the walls and roof. In the case of a building enclosure with a large WWR (greater than 40%), SHGC and U-value of the fenestration system are the two major energy performance characteristics that influence building performance, and tend to dominate the overall building performance (Pope 2011).

2.2.1 U-Value and Frame Effects

U-value is defined as the rate of heat transmission through a building part (e.g. wall or window) per unit area and unit temperature difference. The best-available double-glazed commercial windows are low-e coated, argon gas-filled with fiberglass frame and U-value of less than 0.3 Btu/hr ft^2 F (USI-1.7 W/m^2 K, R-values 3.3 hr ft^2 F/Btu, RSI-0.58 m^2 K/W), and triple-glazed with fiberglass frame and U-value of less than 0.15 Btu/hr ft^2 F (USI-0.85 W/m^2 K, R-7 hr ft^2 F/Btu, RSI-1.23 m^2 K/W) are available (Straube 2014). For aluminum-framed windows, the best-available U-values for double-glazed and triple-glazed windows are approximately 0.35 Btu/hr ft^2 F (USI-2 W/m^2 K, R-2.8 hr ft^2 F/Btu, RSI-0.49 m^2 K/W) and 0.25 Btu/hr ft^2 F (R-4 hr ft^2 F/Btu), respectively.

Lee (2010) performed a series of annual building energy simulations of offices located within the perimeter zones of different orientations, and he concluded that windows with lower U-values provide the greatest energy savings over less insulating windows with higher SHGC for moderate and low internal heat gain offices. After the insulated glazing unit (IGU), he found that the insulating value of the frame has a critical influence on the overall U-value of the window system.

Window frames should be recognized as one of the most critical thermal-bridging components. Most commercial buildings use aluminum as window frame material because of its transitional use, durability, aesthetics, and ability to span over several stories. Although aluminum provides great strength and dimensional consistency for large window area, it has a very high thermal conductivity. Significant thermal loss often occurs through aluminum frames. It is important to minimize this effect by aligning the thermal control (thermal break) of the window frame with the thermal control layer of the wall. Open frame sections should be foam filled to limit additional convection loss as shown in Figure 2-1 (Straube 2014).

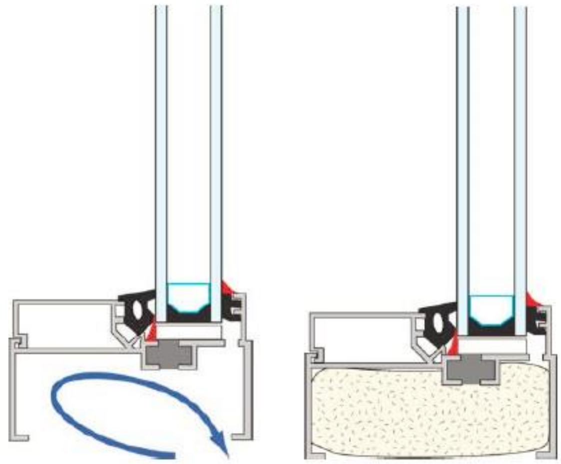


Figure 2-1 Expansion foam is filled inside the open window frame to minimize the thermal-bridging effect (Straube 2014)

2.2.2 Solar Heat Gain Coefficient

The solar heat gain coefficient (SHGC) is a measure of the portion of solar radiation striking a window that enters a room as heat. SHGC is a significant factor in determining the cooling load of many modern commercial buildings (Windows for High-Performance Commercial Buildings 2011).

In Figure 2-2, as the solar radiation strikes the glazing unit, it is either transmitted, reflected, or absorbed in accordance with the window characteristics. The glazing type, the number of glazing units, and glass coatings influence the SHGC. An average value of SHGC for a double-glazed window ranges from less than 20% with highly reflective coatings and absorbing glasses to as high as 80% with uncoated water-white clear glass.

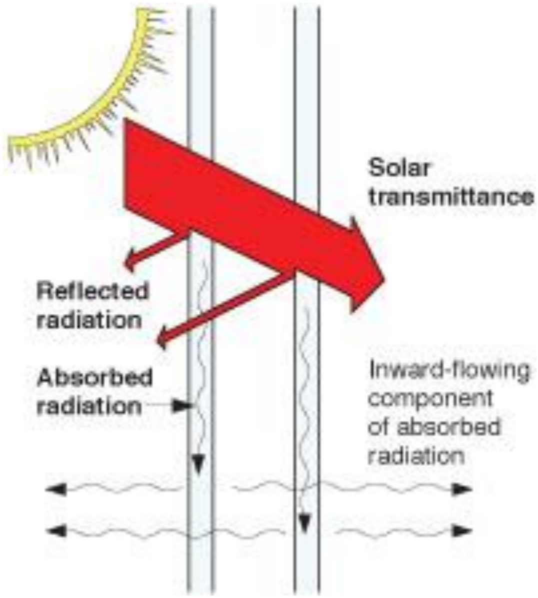


Figure 2-2 SHGC heat flow modes in a glazing unit
(Windows for High-Performance Commercial Buildings 2011)

SHGC consists of three components associated with three areas: 1) the center-glass area, A_{cg}, (the glazed area more than 2.5 inches (63.5 mm) from any sight line), 2) the edge-glass area, A_{eg}, and 3) the frame area, A_{fr}. The combined SHGC value can be calculated by equation 2-1 (Wright 1995):

$$SHGC = \frac{A_{cg}*SHGC_{cg}+A_{eg}*SHGC_{eg}+A_{fr}*SHGC_{fr}}{A_{cg}+A_{eg}+A_{fr}} \qquad \text{Eqn-2-1}$$

Where:
$SHGC_{cg}$ is the solar heat gain coefficient of the center-glass
$SHGC_{eg}$ is the solar heat gain coefficient of the edge-glass
$SHGC_{fr}$ is the solar heat gain coefficient of the window frame

In most cases it is a reasonable assumption that $SHGC_{fr}$ is small enough to be neglected (Wright 1995). However, if $SHGC_{cg}$ is small, A_{fr} is large (i.e., small windows), and dark color frames with high thermal conductivity are used, the solar gain of the frame may exceed the solar gain of the view area (Wright 1999). This is an unlikely situation.

If it is assumed that $SHGC_{eg} = SHGC_{cg}$ (a very common assumption) and $SHGC_{fr} = 0$, equation 2.1 reduces to equation 2.2.

$$SHGC = SHGC_{cg} * \left(\frac{A_{view}}{A_{tol}}\right) \quad \text{Eqn 2.2}$$

Where

$A_{view} = A_{cg} + A_{eg}$

$A_{tol} = A_{cg} + A_{eg} + A_{fr}$

The ASHRAE Advanced Energy Design Guide (AEDG) for small to medium-sized commercial office buildings states that a low SHGC is much more important for low energy use than low U-value for warm climates (Chapter 5, ASHRAE 2011). Higher SHGC and low U-value are both preferable in colder regions (climate zone: 4,5,6,7, and 8), but continuous horizontal overhangs can also be useful to block the high solar gain in summer months.

2.3 Window-to-Wall Ratio

The window-to-wall ratio (WWR) is defined as the ratio of the window area to the total vertical enclosure area. It has a great impact on building performance. The benefits of having highly-glazed buildings (WWR>40%) are that they provide better exterior views for occupants and better access to natural daylighting which increases occupant productivity. While common, these rarely survive fact-based assessments, as high-quality daylighting can easily be achieved with modest WWR (30-40%) and higher levels of glazing (WWR) are routinely associated with comfort complaints due to glare and overheating.

On the other hand, the disadvantages of having highly-glazed buildings (WWR>40%) are:

- Increase heating load due to conduction
- Increase cooling load due to solar gain and conduction

Pope published a presentation on energy codes and design practice (Pope 2011). This presentation focused on industry engagement for high performance buildings and integrated design processes in cold climates. He concluded that fenestration specifications dominate building performance, and asserted that the recommended WWR for lowest energy use should be 17% for commercial and institutional buildings in Toronto.

In cold climates, incremental daylighting savings diminish with increasing WWR such that highly glazed buildings (WWR>40%) do not save more from daylighting energy than they lose in heat transfer (Johnson et. al. 1984). Straube (2014) finds that the WWR dramatically influences the ability of the overall vertical enclosure to resist heat loss, and asserts that high performance commercial buildings should have WWR of 20 to 40% because of the desire for views and natural light.

The WWR is an orientation-sensitive factor that plays a significant role in the building enclosure design. Large window area can be used to allow more visible light into the building as long as solar heat gain and conduction problems are not excessive.

AEDG suggests that for any selected WWR between 20% and 40%, the recommended combinations of U-factor and SHGC shown in Figure 2-3 can contribute toward the 50% energy savings target of the entire building. Significant reductions of WWR on the east and west sides can further reduce energy consumption while maintaining consistency with regard to needs for view, daylighting, and passive solar strategies (Chapter 5, ASHRAE 2011).

CZ	U-Factor	SHGC	VT	Glass and Coating	Gas	Spacer	Frame
1-3	0.46	0.23	0.51	Double clear, highly selective low-e coating		Standard	Broken aluminum
1-3	0.47	0.24	0.32	Double clear, low-e reflective coating		Standard	Broken aluminum
1-3	0.32	0.20	0.29	Double clear, low-e reflective coating		Standard	Foam-filled vinyl or pultruded fiberglass
4-5	0.34	0.25	0.51	Double clear, highly selective low-e coating	Argon	Insulated	Broken aluminum
4-5	0.35	0.22	0.32	Double clear, low-e reflective coating	Argon	Insulated	Broken aluminum
4-5	0.32	0.20	0.29	Double clear, low-e reflective coating		Standard	Foam-filled vinyl or pultruded fiberglass
6-7	0.31	0.39	0.50	Triple clear, low-e coating for outer light only	Argon	Insulated	Broken aluminum
6-7	0.26	0.31	0.54	Double clear, low-e selective coating	Argon	Insulated	Foam-filled vinyl or pultruded fiberglass
8	0.25	0.39	0.53	Triple clear, low-e coating for outer and second lights	Argon	Insulated	Aluminum thermally isolated frame
8	0.22	0.36	0.53	Triple clear, low-e coating for outer light only	Argon fill both spaces	Insulated	Foam-filled vinyl or pultruded fiberglass

CZ = climate zone

Figure 2-3 Recommended U-value and SHGC for 50% energy savings by AEDG (ASHRAE 2011)

Sullivan (1992) completed research on a method for optimizing solar control and daylighting performance in commercial office buildings. The prototypical office building module was located in Los Angeles with WWR ranging from 0% to 70% of the floor-to-floor wall area. The glass specifications were double-glazing with a fixed U-value of 0.55 Btu/hr ft^2 F (3.13 W/m^2 C), shading coefficient varying between 0.20 and 0.95, and visible transmittance ranging from 0.10 to 0.88. Sullivan concluded that the total electricity consumption of core and perimeter zones combined due to cooling, fan energy, lighting, and plug load increases linearly with increasing WWR as shown in Figure 2-4 from (Sullivan 1992).

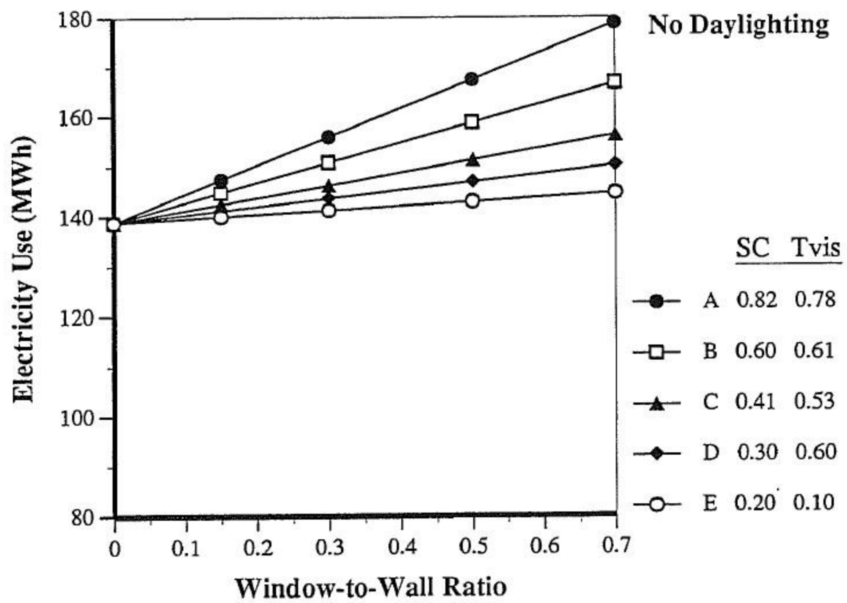


Figure 2-4 Total electricity consumption increases linearly with WWR (T_{vis} = visible transmittance and SC = SHGC of windows)

Reducing WWR not only lowers the total electricity consumption, but also lowers the perimeter zone peak heating load in commercial buildings. Love (2008) performed a study on peak heating load vs. WWR. A 10-story commercial building located in a cold climate was examined. Love found that WWR should be limited to 40%, and the simulation results show that the building peak heating load is reduced by approximately 25% by changing WWR from 70% to 40% as shown in Figure 2-5 (Love 2008).

	Component Load (W)	
Peak Load Component	**70% Glass, Base**	**40% glass, Base**
Wall Conduction	62	124
Window Glass + Frame Conduction	675	390
Window Glass Solar	0	0
Occupants to Space	0	0
Light to Space	0	0
Equipment to Space	23	23
Infiltration	158	158
Total	918	695

Figure 2-5 Significant saving on the peak heating load with reduction in WWR (Love 2008)

2.4 Insulation

Increasing the insulation level is an important and obvious step to reduce energy transfer through the building enclosure. According to the heat transfer equation 2-3, the R-value governs the total heat transfer through the building enclosure.

$$\dot{q_{loss}} = \frac{A(t_{in} - t_{out})}{R} \qquad \text{Eqn 2-3}$$

Achieving high insulation levels of wall, roof, and floor should be carefully considered, not just adding more insulation and increasing thickness. Designers may intentionally specify higher assembly R-values to offset the heat loss caused by conduction, thermal bridging, and air leakage. Increases in assembly R-values however lead to a higher capital cost. Therefore, it is important to determine the most cost effective insulation level of the building enclosure, especially for high performance buildings.

The rising cost of energy, concerns of climate change/pollution, and demands for increased comfort have led to the desire for increased insulation levels in many new and existing buildings. Straube emphasized the importance of high R-value enclosures in a report for the US Department of Energy, and concluded that higher thermal resistances could reduce energy consumption for space heating in all climate zones (Straube 2011).

Blum summarized required insulation levels for above-grade construction. He proposed recommended R-values for roofs and above-grade walls for commercial buildings and residential houses as shown in Figure 2-6 and concluded that the increased values showed a clear path of high insulation building enclosure for the designers who comply and even exceed the standard practices (Blum 2007).

6. Approved Building Envelope Changes for Climate Zone 6 (Minneapous and Maine)						
	Nonresidential		Residential		Semi-Heated	
Opaque Elements	**Current**	**Proposed**	**Current**	**Proposed**	**Current**	**Proposed**
Roofs						
Insulation entirely above deck	R-15 ci	R-20 ci	R-15 ci	R-20 ci	R-5 ci	R-10 ci
Metal Buildings	R-19	R-13 + R-19	R-19	R-13 + R-19	R-10	R-16
Attic and other	R-38	NC	R-38	NC	R-38	R-30
Wall, above-grade						
Mass	R-9.5 ci	R-13.3 ci	R-11.4 ci	R-15.2 ci	NR	R-5.7 ci
Metal Building	R-13	R-13 + R-13	R-13 + R-13	NC	R-13	NC
Steel-framed	R-13 + R-3.8 ci	R-13 + R-7.5 ci	R-13+R-7 ci	NC	R-13	NC
Wood-frame and other	R-13	R-13 + R-7.5 ci	R-13 + R-3.8 ci	R-13 + R-7.5 ci	R-13	NC

Figure 2-6 Proposed R-values for above-grade building enclosure (Blum 2007), ci means continuous insulation

The province of Ontario has adopted its first set of energy codes for residential and commercial buildings in 2006. A more recent energy code specifies the minimum insulation values for above-grade walls as shown in Figure 2-7 (Ontario Building Code (OBC) 2012).

	Climate Zone 6 (4000 ≤ HDD < 5000)		
	Nonresidential	Residential	Semiheated
Mass Walls, R-value (ICFs)	15.2ci	20.0ci	9.5ci
Metal Framed, R-value	13.0cav + 10.0ci	13.0cav + 10.0ci	13.0cav + 3.8ci
Metal Building, R-value	13.0cav + 13.0ci	13.0cav + 13.0ci	13.0cav + 6.5ci
Wood Framed & Other, R-value	13.0cav + 10.0ci	13.0cav + 10.0ci	13.0cav + 3.8ci

Figure 2-7 Minimum insulation values for above-grade walls (OBC 2012), (cav means framing cavity, ci means continuous insulation)

2.5 Ventilation and Air Leakage

Occupant health is a main concern while designing the ventilation system. Ventilation (air exchange rate) is defined as "the process of supplying air to or removing from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space" (Chapter 16, ASHRAE 2013).

There are two ways to provide ventilation to a space: natural ventilation and mechanical (forced) ventilation. Natural ventilation is flow of air through open windows, doors and grilles, and any other opening driven by the natural forces of wind and buoyancy. It is hard to measure and provide sufficient fresh air to the space through natural ventilation because of the variability and unpredictability of natural forces. Exhaust/supply fans drive the mechanical ventilation that creates a negative/positive pressure within the building as the fans expel/inject air. The reduced/increased pressure causes fresh air to be drawn/blown into the building. The pressure difference between the inside and the outside of the building is the potential that fans must overcome to move air through the building (Clarke 2006). The required ventilation flow rate is dependent on the number of occupants, the floor area, and the type of occupancy, and can be estimated using Equation 2-4. Equation 2-5 is an approximate calculation of the sensible load for the ventilation. It is derived from a more fundamental energy balance, and it is assumed that the humidity ratios of indoor and outdoor air are equal (i.e., it excludes the latent portion of the ventilation load).

$$Q_v = (R_p n_p + R_a A_{floor})/E_z \qquad \text{Eqn 2-4}$$

Where:

R_p is people outdoor air rate in l/s-person

n_p is the number of people

R_a is the outdoor air rate per unit area in l/s-m^2

A_{floor} is the total exterior floor area in m^2

E_z is the zone air distribution effectiveness, ranging from 0.5 to 1.2

$$q_s = 1.21 * Q_v * (T_{out} - T_{in}) \qquad \text{Eqn 2-5}$$

Where:

1.21 has an unit of $\frac{W}{\frac{L}{s}*℃}$

q_s is the sensible heat load in W

Q_v is the required ventilation rate in l/s

T_{out} is the outdoor air temperature in ℃

T_{in} is the indoor air temperature in ℃

The air flow rate per person, R_p, and air flow rate per unit floor area, R_a, are important in order to maintain a healthy and comfortable environment at the least energy penalty. ASHRAE, in the commonly specified Standard 62, has defined a list of minimum levels of air flow rates for each individual building type.

Air tightness influences the ventilation performance. Air leakage is a common phenomenon in buildings constructed in the past, and still occurs in air-tight buildings (high performance buildings). Air leaks through windows, doors, and cracks in the wall and roof. This can account for a significant portion of the thermal space-conditioning load, and affects occupant comfort and indoor air quality. It is difficult to eliminate air leakage. ASTM standard E779-03 provides a method to determine the air leakage rate by fan pressurization after the building is constructed. This test method consists of mechanical pressurization or de-pressurization of a building and measurements of the resulting air flow rates at given indoor-outdoor static pressure differences (ASTM 2010).

2.6 Automatic Building Control System

Modern commercial buildings are designed by architects using highly glazed facades to provide appealing-working environments. It is important to consider and manage solar heat gain because it is a significant heat input to the building that contributes to summertime peak cooling loads. There are some practical methods to minimize the building loads while keeping the working environment comfortable: 1) installing high performance, low solar gain, glazing system, 2) using shading device(s), and 3) implementing an advanced automatic building control system (e.g., operable shading system, lighting control, and ventilation control). Improving solar control in buildings to reduce peak cooling loads not only lowers the annual electricity costs for owners, but also reduces the cost of cooling equipment and the significant cost to construct and maintain the power distribution grid and generating capacity.

Many research labs and institutions have focused on the effects of different shading locations and shading materials. The University of Waterloo Advanced Glazing System Laboratory (AGSL) has developed a set of practical and flexible models to demonstrate the shading layer properties and the interaction of shading layers with a glazing system. In 2009, AGSL successfully implemented shading models into ESP-r (building modeling program) in the form of the Complex Fenestration Construction (CFC) to offer the capability of modeling glazing/shading systems with any combination of shading/glazing layers. The fundamental strategy for the implementation is the design of a new multi-layer construction within ESP-r. The ESP-r CFC slat blind model was compared with the EnergyPlus 2.0 model with double glazed windows for hourly cooling loads for outdoor, between-glass, and indoor blind cases, and results were similar (Lomanowski 2009).

An automatic building control system coupled with operable shades is a practical method to control solar heat gain, thermal conduction to a lesser extent, and lighting to reduce peak cooling loads in summertime. External and internal lighting sensors, occupant sensors, thermal sensors and a fully operable shading system are the key features for an automatic building control system.

An outdoor operable slat-type shading is a popular design option in European countries, but not in Canada. Users must operate traditional outdoor shading devices manually, but it is not practical to manually adjust the outdoor shading to full advantage. However, an operable shading system can be integrated with the central control system, allowing the shading device to be adjusted continually to avoid direct beam radiation while maximizing the diffuse light for daylight savings in the cooling season, or maximizing solar transmission to reduce heating load. Therefore, an automated outdoor shading system not only has the same features as manual outdoor shading, but also provides the ability of tracking the incident angle of sunlight, while monitoring indoor temperature to automatically adjust the shading for better energy efficiency. Automatic control makes it possible to reduce both cooling and heating space load.

Building designers often avoid using outdoor operable shading systems in North America because of perceived obstacles associated with reliability, capital cost and maintenance. Few studies have focused on the outdoor operable shading device in North America, but there are some existing high performance buildings that use outdoor operable shading system.

The Enermodal Engineering Ltd. (now part of MMM) headquarters located in Kitchener Ontario is equipped with an automatic building control system, including operable outdoor shading. The operable shading system, roller blinds in this case, can open and close according to the incident angle of the sunlight and the indoor temperature. Also, indoor slat shading is installed that allows occupants to manually adjust the brightness and glare. Every conditioned zone is able to access the natural lighting, and occupant sensors are installed to control internal lighting. The windows are triple glazed.

Another example is the Loyola University Richard J. Klarchek Information Commons Building in Chicago. It is a library-like place for students to study and work on research. This building includes advanced mechanical systems and visually stunning architectural features. One of the features is the operable outdoor slat-type shading. The shading devices are installed on the west façade of the building. An outdoor light sensor triggers the deployment of the blinds. The computing system determines the angle of the slats, according to the sun's location, to preclude direct beam solar transmission while maximizing diffuse transmission light for daylighting. On the east façade, automated indoor roll-up blinds are used to minimize solar heat gain (Mclauchlan & Lavan 2010). The article does not specify the percentage of saving due to the operable shading system; however, with the advanced technologies and innovative designs (excluding plug load and process loads), the building energy performance is reported to be 46% better than the ASHRAE Standard 90.1-1999 base building or about 10% less than the current ASHRAE 90.1-2010 (Mclauchlan & Lavan 2010).

2.7 Daylighting

In high performance building evaluation, daylighting performance has become one of the critical parameters. Daylighting is important because it fulfils basic human requirements: to be able to see a task and the space well, and to experience some environmental stimulation (Boyce 1998). It also helps to save electrical energy when lights are turned off. In addition, daylight is important to occupants for its quality, spectral composition, and variability. Long-term electrical lighting is believed to be deleterious to health; working by daylight is believed to produce less stress and discomfort (Rusak 1995). Proper design of a daylighting system provides a number of benefits: lighting quality, comfort for occupants, increase in productivity, and potential reduction of lighting demand and cooling load. These factors are reviewed below.

2.7.1 Lighting Quality

Extraterrestrial sunlight consists of a spectrum from infrared to ultraviolet. Natural light at ground level (solar spectral distribution) has a similar spectral distribution, but electrical light has a limited spectral range. Natural light intensity and contrast ratio often present problems for daylighting design, especially during sunrise and sunset. Tinted windows are sometimes used to reduce the effect of light intensity. In places that have high contrast ratios, electrical lights can be used. Good daylighting design provides a better lighting quality by enhancing colour discrimination and is better suited to human vision (Enermodal 2002).

2.7.2 Occupant Comfort

Previous studies indicate that daylighting provides physiological benefits, and work by daylight entails less stress and discomfort (Rusak 1995). Occupants exposed to exterior views (i.e., surroundings, and natural light) experience reduced visual and mental stress. Hospital patients located near windows recuperate more rapidly than those farther away from daylight and outdoor views (Garris 2004).

2.7.3 Increase in Productivity

Occupants with outdoor views and natural light improve concentration, work more efficiently, and make fewer mistakes (Enermodal 2002). Schools with daylighing report better test scores, and big-box retail stores with daylighting generate more revenue per square foot and a good daylighting design can provide up to 20 percent better productivity according to a research study at Carnegie-Mellon (Garris 2004).

2.7.4 Reduction on Lighting Demand

Deploying daylighting with proper electric lighting controls is a practical method to reduce electrical lighting demand, and associated cooling load. Reducing the lighting demand not only lowers the operational cost, but also lowers the carbon dioxide generated from electrical power generation. Figure 2-8 shows that lighting represents approximately 27% of the total energy consumed in commercial buildings in Ontario (Burton 2008). US Department of Energy states that lighting represents up to 40% of the total energy consumption in commercial buildings as shown in Figure 2-9 (DOE 2014).

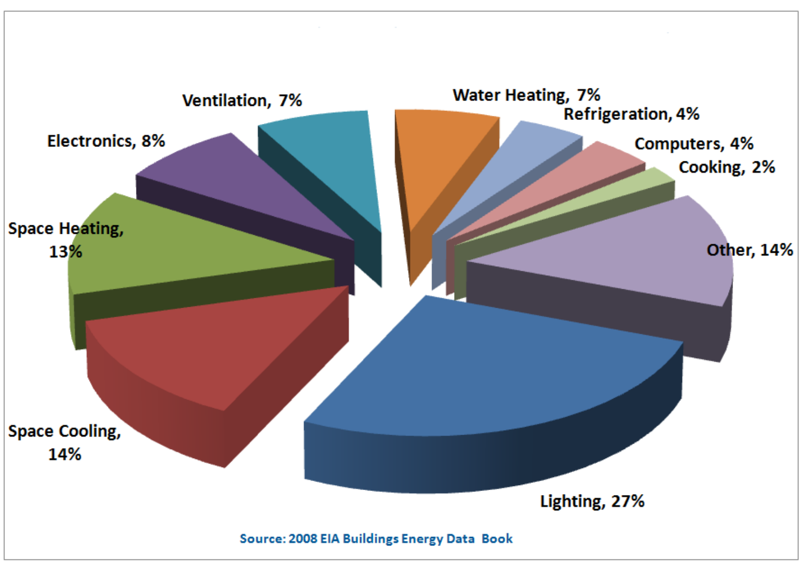


Figure 2-8 Building energy consumption breakdown in Ontario for commercial buildings

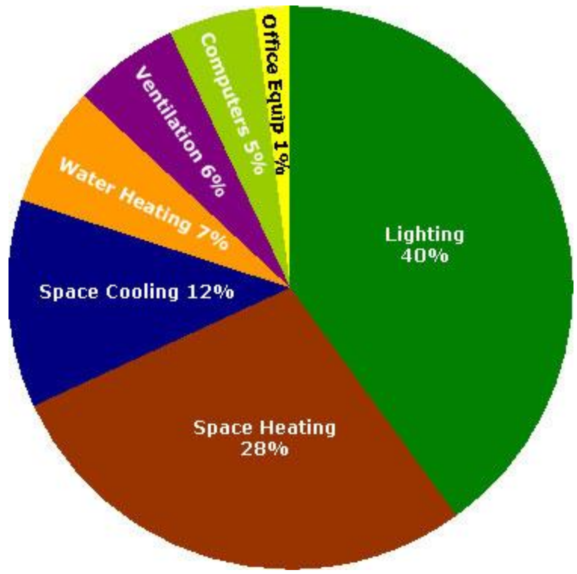


Figure 2-9 Significant lighting energy consumption for commercial buildings analyzed by (US Department of Energy 2014)

Outdoor lighting sensors, occupancy sensors, and lighting control systems are three main components that should be integrated. An occupancy sensor can turn off lights when a zone is unoccupied. The central lighting control system calculates the time of a day, the incident angle of the sun and the light intensity detected by the outdoor lighting sensor, then decides to turn on/off the electric light. Without proper electric lighting controls, daylighting saves zero energy. For example, if no one is in the zone, and the occupancy sensor signals the zone as occupied, the electric light will be turned on, which results in zero energy savings. In order to fully use the advantage of daylighting, daylighting and electrical lighting control strategies have become more important and popular in commercial building design. Study shows that good glazing performance and design optimization with daylighting can reduce the lighting power consumption (Johnson et. al. 1984).

An increase in glazing area in the commercial/institutional sector (i.e., increased WWR) results in higher heating and cooling loads. ASHRAE 90.1 limits the lighting power density allowance as shown in Table 2-1. Required power density has been reduced by an average of 32% due to improvements in lighting technology (i.e. efficiency) between 1999 and 2010. The lighting power density will be further reduced as lighting technology improves (i.e., as compact fluorescent lamp (CFL) and light emitting diode (LED) lighting replaces incandescent). Hence, daylighting will be less important as a strategy for energy saving.

Table 2-1 ASHRAE Standard 90.1 lighting power allowances based on floor area

Building Type	Maximum Lighting Power Density (W/sq.ft.) Allowed of the ASHRAE/IES 90.1 Standard			
	1999/2001	**2004/2007**	**2010**	**Reduction (1999-2010)**
Automotive Facility	1.5	0.9	0.982	35%
Convention Center	1.4	1.2	1.08	23%
Office	1.3	1	0.9	31%
Post Office	1.6	1.1	0.87	46%
Retail	1.9	1.5	1.4	26%
School/University	1.5	1.2	0.99	34%
Average (area-weighted)				32%

2.8 Climate Zone

Climate zone is a well-known factor that influences building design decisions. Climatic information is commonly used for set enclosure insulation level, glazing selection, and sizing equipment for heating and cooling. A building enclosure design should be based on the climate zone where the building is located.

There are two popular methods to define Canadian climate zones using ASHRAE 90.1, which is similar to National Building Code of Canada (NBCC), and Natural Resource Canada (NRC 2014). ASHRAE 90.1 defines climate zones for the North America Region from 1-8 as shown in Figure 2-10 and Table 2-2 lists the climate description for each zone.

Figure 2-10 North America Region climate zone by ASHRAE Standard 90.1 (reproduced from ATLAS Building Forward (ATLAS 2014))

Table 2-2 North America climate zone definition by ASHRAE Standard 90.1North America climate zone definition by ASHRAE Standard 90.1

Zone Number	Name	Thermal Criteria
1	Very Hot-Humid (1A), Dry (1B)	5000 < CDD10^{0}C
2	Hot-Humid (2A), Dry (2B)	3500 < CDD10^{0}C ≤ 5000
3A and 3B	Warm-Humid (3A), Dry (3B)	2500 < CDD10^{0}C ≤ 3500
3C	Warm-Marine	CDD10^{0}C ≤ 2500 and HDD18^{0}C ≤ 2000
4A and 4B	Mixed-Humid (4A), Dry (4B)	CDD10^{0}C ≤ 2500 and 2000< HDD18^{0}C ≤ 3000
4C	Mixed-marine	2000 < HDD18^{0}C ≤ 3000
5A, 5B and 5C	Cool-Humid (5A), Dry (5B), Marine (5C)	3000 < HDD18^{0}C ≤ 4000
6A and 6B	Cold-Humid (6A), Dry (6B)	4000 < HDD18^{0}C ≤ 5000
7	Very Cold	5000 < HDD18^{0}C ≤ 7000
8	Subarctic	7000DD18^{0}C

* CDD is cooling degree days, and HDD is heating degree days.

Energy Star divides Canada into four zones as shown in Figure 2-11. Zone A is the hottest and Zone D is coldest. The average HDD for each zone is listed in Table 2-3 (NRCan 2014):

Figure 2-11 Climate Zones of Canada (NRCan 2014)

Table 2-3 Canadian climate zone definition by Energy Star, based on heating degree days (HDD)

Zone Number	Thermal Criteria
A	$\leq$ 3500 HDD18^{0}C
B	3500 < HDD18^{0}C $\leq$ 5500
C	5500 < HDD18^{0}C $\leq$ 8000
D	> 8000 HDD18^{0}C

Advanced Energy Design Guide (AEDG) recommends the following strategies of building designs for different climate zones (Chapter 4, ASHRAE 2011):

- Hot and humid climates: “the primary driving forces in these areas are conduction, solar gain through windows, and cooling energy associated with removing internal moisture due to people latent loads. Therefore window areas, orientation, and shading are critical. The common goal/solution is to reduce the solar gain as much as possible by selecting low SHGC windows and installing shading systems".

- Hot and dry climates: "the primary driving forces in these areas are conduction, solar gain through windows, and cooling energy associated with ventilation air." The established solution is to choose low SHGC windows, solar-reflective roofs and walls.
- Mild and humid climates: "the primary driving forces in these areas are conduction, solar gain through windows and cooling energy associated with removing moisture due to ventilation and infiltration. Because these areas are exposed to snow and freezing precipitation in the winter, the building system should be optimized to function efficiently". The established solution is to reduce heat transfer and solar gain through the building enclosure, especially the fenestration system.
- Cold and dry climates: "the primary driving forces in these areas are heat loss through the building enclosure and heating and cooling loads associated with ventilation air". The established solution is to increase the insulation of windows, roofs and walls, and pressure difference across the building enclosure should be near zero to avoid driving vapour into the wall construction.
- Cold and humid climates: "The primary driving forces in these climates are heat loss through the building envelope, heat loss due to infiltration, and attention to heating and cooling loads associated with ventilation air." The established

solution is to increase the insulation of the building enclosure to reduce the conduction loads, and reduce infiltration loads.

In summary, for hot climate zones, excess heat gains by conduction and solar radiation are important considerations while designing the building enclosure. For cold climate zones, heat loss through the building enclosure is the primary reason for increased heating load. Solar radiation is an important and useful source to offset the heating load for small and medium-sized buildings, especially in an extreme cold climate zone (zone above 6 by ASHRAE 90.1). In the case of humid climate zones, cooling energy associated with removing internal moisture due to people latent loads, and heating and cooling loads associated with ventilation air should be considered. Figure 2-12 shows established solutions to deal with these situations.

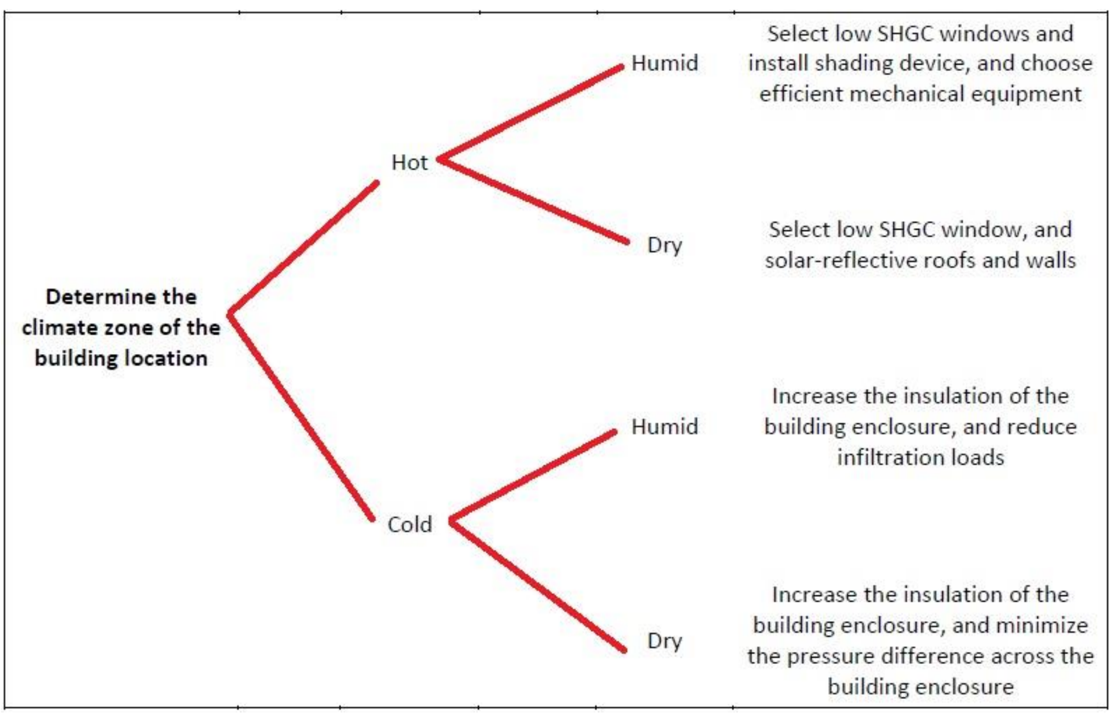


Figure 2-12 Established solutions to deal with climate zones in North America

2.9 HVAC Systems

HVAC systems typically have three main functions: satisfying heating or cooling loads, delivering outdoor air to the building, and removal of moisture. Designers may often forget the primary purpose of HVAC systems is to provide comfortable environments for the building occupants. Sometimes, identifying the balance point between comfort and energy savings can be difficult.

Variable air volume (VAV) and constant air volume (CAV) systems are commonly used to deliver conditioned air to a space. A VAV system can change the volumetric rate of air delivery to a space depending on the amount of heating/cooling or ventilation required. A CAV system is less efficient because additional fan power is required to keep the CAV system operating at a constant flow rate, and often consumes more electric power than needed, but a constant supply of fresh air is easy to accomplish. A VAV system can provide temperature satisfaction for each building occupant and avoid the energy waste of any overheating or overcooling (Dodd 2012), but changing the proportion of fresh air in the supply can make it difficult to account for the changes in flow rate demanded by the thermostat. CAV systems are rarely specified for new buildings because of their energy penalty, and the hoped for savings of VAV systems have been fraught with challenges such as complex control issues or reduced indoor air quality.

Providing outdoor air and conditioned air are two different concepts, and sometimes they contradict each other. For instance, on a sunny winter day, an occupied office building may require a small amount of heating but a significant amount of ventilation. At night, an un-occupied office building may require a significant amount of heating but little ventilation. VAV systems should be able to identify these situations to prevent overheating or overcooling. The control algorithms for VAV system become more complicated as building sizes increase (Hanam 2010). A dedicated outdoor air system (DOAS) is a system that conditions and delivers fresh air separately from the heating and cooling, which simplifies the control required and provides assurance that outdoor air requirement is met. Thermostats are implemented for each individual zone to control the temperature, and ventilation can be also be controlled by zone using occupancy and/or carbon dioxide sensors. The heating and cooling can easily be provided by more than air-based systems when a DOAS provides ventilation: water-based, refrigerant-based or thermally-active building surfaces are all low-energy options that can now be considered.

2.10 Conclusion

Major building design parameters that strongly affect building performance at the early design stage are described in detail in Chapter 2. Determining the factor(s) that affects the building performance for a particular project at the early design stage is important. In Chapter 3, methods of calculation regarding to design parameters are explained in detail.

3.0Development of Load Model

This chapter documents the development of a single zone Excel-Based Load Model (EBLM). As shown in Table 3-1, the EBLM consists of three parts – inputs, load calculations, and the outputs. Weather, building specifications, schedules, internal heat generation data, shading, and factors for dynamic heat flow conduction are input variables created to allow users to modify the el. Once inputs are entered, EBLM is run to calculate the outputs (building loads), which can be broken down into following components: lighting, plug loads, occupants, ventilation, air leakage, windows, walls, roof, total heating load and total cooling load.

Table 3-1 Overview of EBLM structure

Inputs		Outputs
Weather Data		Lighting
Building Specifications		Plug Loads
Operating Schedules		Occupants
Internal Heat Generation		Ventilation
Shading	**Calculations**	Air Leakage
CTS and RTS Factors		Windows
		Walls
		Roof
		Heating Load
		Cooling Load

3.1 Inputs

Users are required to enter only the most basic data for building enclosure specifications, building operation schedules, internal heat generation, shading specifications – all of interest for early stage design. Data, including hourly weather data for an entire year, and dynamic response factors for enclosure (CTS) and building (RTS) are also required, but can be copied from standard sources. Screenshots of input are shown in Appendix A.

3.1.1 Weather Data

The required weather data includes hourly data of outdoor dry and wet bulb temperatures (°F or ℃), solar flux on the horizontal surface (Btu/hr ft^2 or W/m^2), and wind speed (knots, MPH, or km/h). If the weather data is in imperial units, it will be converted into SI units. These data can be obtained from online sources for EPW files (http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm), weather stations near the site, and even databases from other simulation programs (e.g. eQUEST, Energyplus).

3.1.2 Building Specification

EBLM simplifies the input of building enclosure specifications. Table 3-2 summarizes the building specifications that must be entered by the user.

Table 3-2 Required Inputs for building specifications

Specification	Note
Location	Detailed location of the building model and solar calculation constants
Dimensions	Plan dimensions, floor-to-floor height, WWR etc.
Sol-air Property	Required variables for sol-air calculation
Structure	walls and roof (e.g., brick, concrete), and the structure of the building model (e.g., light, medium, or heavy) for dynamic heat flow calculations (i.e. CTS and RTS data)
Wall and Roof	R-values for walls and roof, and the orientations of walls
Glazing Specification	Glazing property for windows and doors (e.g., U-value, SHGC)
Ventilation and Air Leakage	Volume flow rate for ventilation and air leakage

3.1.3 Operating Schedules

Operating schedules include the operation hours for lighting, plug load, occupant, and ventilation in EBLM. Operating schedules contain hourly profiles, which represent hourly load usage for every hour. The user can estimate the hourly load usage from 0% - 100% at the early design stage.

3.1.4 Internal Heat Generation Data

Tables 3-3 to 3-5 show the inputs required for internal heat generation. Users can specify the radiative and convective fractions of internal heat generation components, number of occupants, and sensible and latent heats for occupancy. Similarly users are required to enter values for plug load and lighting according to building standards or design requirements.

Table 3-3 Occupant input parameters

Occupancy Information	Default Values	Note
Radiative Fraction	0.6	Radiant fraction of occupancy sensible heat gain
Number of Occupants	135	
Sensible Portion (W)	70	Instantaneous cooling load, may be modified for specific situation
Latent Portion (W)	45	Moisture, may be modified for specific situation
Heat Generated per Occupant (W)	115	Sum of the sensible and latent portions
Occupancy Schedule		Specified by schedule data

Table 3-4 Plug load input parameter

Plug Load Information	Default Values	Note
Radiative Fraction	0.4	Radiant fraction of plug load heat gain
Plug Loads (W/m^2)	9	Specify according to design or code maximum
Plug Loads Schedule		Specified by schedule data

Table 3-5 Lighting input parameters

Luminaire Type: Recessed fluorescent luminaire without lens, in-ceiling type	Default Values	Note
Radiative Fraction	0.48	Radiant fraction of lighting heat gain
Lighting Power Density (W/m^2)	9.7	Required to be specified according to design or code maximum
Lighting Schedule		Specified by schedule data

3.1.5 Shading

The shading parameter is designed for users who desire a tool to simulate the effects of various shading types, locations, and control strategies for the operable shading system. Four types of shades can be modeled – slat-type, drapery, roller, and insect screen. Three possible locations for shades are: indoor, interstitial, and outdoor. Users are required to specify the type and location of the shading system as shown in Table 3-6 (this is a pull down menu). Outdoor, interstitial, and indoor locations are shown in Figure 3-1. If users prefer to simulate the building performance without the shading system, the type of shading system should be specified as N/A.

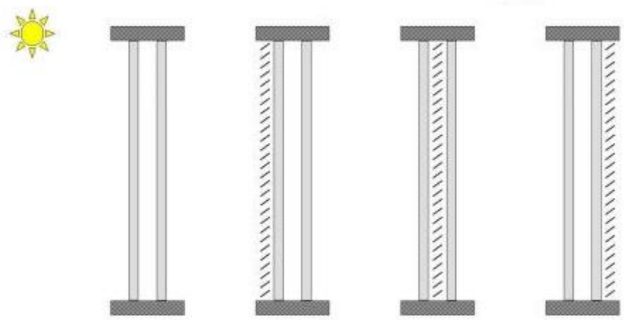


Figure 3-1 Available shading locations, from left to right: no shade, outdoor, interstitial, and indoor (Bean 2012)

Table 3-6 Defining a shading system and location

Defining the Shading System	Pull Down Menu	Options
Type	N/A	Slat-type, drapery, roller, and insect screen
Location*	N/A	No shade, indoor, interstitial, and outdoor

* In reality slat-type shading can be used in indoor, interstitial, and outdoor location; drapery and roller are used in indoor location; and insect screen can be used in interstitial and outdoor location.

If users prefer to have a fixed shading system, the *operable shading* tab is left as N/A under control strategy, as shown in Table 3-7 (a pull down menu is used to select the control strategy). To consider the impact of operable shading, the user only needs to specify the control strategy. There are three available control strategies– outdoor temperature, solar incident intensity, and combination of outdoor temperature and solar incident intensity:

- The outdoor temperature control strategy is based on an outdoor temperature limit. If the outdoor temperature is higher than the specified value, then the shade will be closed.

- The solar incident intensity control strategy is based on incident solar flux (sum of direct, sky diffuse and ground reflective radiation) striking each wall. If the solar flux exceeds a specified limit, then the shade will be closed. Each orientation is considered independently.
- The third control strategy is the combination of outdoor temperature and incident solar flux. The shading system will be opened if the outdoor temperature or solar flux is within the specified limit. More specifically the shade is closed if both outdoor temperature and solar incident intensity are above their respective limits.

Table 3-7 Operable control strategy interface

Control Strategy	Default Value	Unit	Note
Operable Shading Based on	N/A		Option for users to identify the operable shading system control strategy
Outdoor Temperature Limit	7	℃	Allowable outdoor temperature for temperature below which shade is opened
Solar Intensity Limit	400	W/m^2	Allowable wall surface solar flux (direct, diffuse, and reflected) below which shade is opened

Lastly, users need to identify properties of the selected shading system based on options summarized in Tables 3-8 to 3-11. Values for these parameters for specific systems can be obtained from the ASHRAE Handbook of Fundamentals (Chapter 15, ASHRAE 2013). Note: IAC is define as $IAC = SHGC_{shaded}/SHGC_{unshaded}$.

Table 3-8 Slat-type shading specification

Slat-Type	Default Value	Note
Number of glazing layers	3	Specified on the building specification tab
Low-e	0.05	Low emissivity coating, be specified on the building specification tab
IAC_0	0.04	IAC at normal incidence
IAC60	0.02	IAC at profile angle of 60 degree
IAC_{diff}	0.13	IAC with respect to diffuse insolation
Operable Shading System		
Number of glazing layers	3	Specified on the building specification tab
Low-e	0.05	Low emissivity coating, be specified on the building specification tab
Slat angle	45	Slat angle used when the shading device is closed to block direct solar transmission
IAC_0 when open	0.94	IAC at normal incidence when the shade is open
IAC_{60} when open	0.99	IAC at profile angle of 60 degree when the shade is open
IAC_{diff} when open	0.44	IAC with respect to diffuse insolation when the shade is open
IAC_0 when close	0.07	IAC at normal incidence when the shade is closed
IAC_{60} when close	0.14	IAC at profile angle of 60 degree when the shading is closed
IAC_{diff} when close	0.48	IAC with respect to diffuse insolation when the shade is closed

Table 3-9 Drapery shading specification

Drapery	Default Value	Note
Number of glazing layers	3	Specified on the building specification tab
Low-e	0.05	Low emissivity coating, be specified on the building specification tab
IAC	0.68	IAC with respect to beam insolation
IAC_{diff}	0.68	IAC with respect to diffuse insolation

Table 3-10 Roller shading specification

Roller	Default Value	Note
Number of glazing layers	3	Specified on the building specification tab
Low-e	0.05	Low emissivity coating, be specified on the building specification tab
IAC	0.68	IAC with respect to beam insolation
IAC_{diff}	0.68	IAC with respect to diffuse insolation

Table 3-11 Insect screen shading specification

Insect Screen	Default Value	Note
Number of glazing layers	3	Specified on the building specification tab
Low-e	0.05	Low emissivity coating, be specified on the building specification tab
IAC	0.6	IAC with respect to beam insolation
IAC_{diff}	0.6	IAC with respect to diffuse insolation

3.1.6 CTS and RTS Factors

The CTS and RTS data are used in simplified methods that are derived from the heat balance method. These methods are used to perform heat gain and space load calculations (Chapter 18, ASHRAE 2013). The CTS and RTS section of EBLM includes four 24-hour time-related sets of CTS and RTS distribution data. Conduction time factors are response factors that are derived by first calculating the conduction transfer function. Figure 3-2 shows five examples of wall CTS factors. a total of four options are given in EBLM, or users may enter their own CTS and RTS factors to match desired types of building component. The other three sets of factors are roof CTS, nonsolar RTS factors (used to account for all heat gains except solar transmission), and solar RTS factors (is used for solar transmission). These sets of factors can be found in Appendix A. CTS and RTS factors for a wide range of situations can be found in the ASHRAE Handbook of Fundamentals (Chapter 18, ASHRAE 2013).

	A	B	C	D	E	F
1	Wall Conduction Time Series (CTS)					
2	**Wall Number**	1	2	3	4	5
3	**Wall Type**	Curtain Wall	Stud Wall	Brick Wall	Concrete Block Wall	Precast and Cast-in-Plate Concrete Wall
4	**Total R (m2K/W)**	2.3	2.5	2.9	3	3.8
5	**Hour**	**Conduction Time Factors (%)**				
6	**1**	25%	7%	2%	1%	2%
7	**2**	57%	44%	2%	1%	2%
8	**3**	13%	32%	2%	5%	3%
9	**4**	3%	12%	3%	9%	3%
10	**5**	0%	4%	5%	11%	5%
11	**6**	0%	1%	6%	10%	5%
12	**7**	0%	0%	7%	9%	6%
13	**8**	0%	0%	7%	8%	6%
14	**9**	0%	0%	7%	7%	6%
15	**10**	0%	0%	7%	6%	6%
16	**11**	0%	0%	6%	5%	6%
17	**12**	0%	0%	6%	4%	5%
18	**13**	0%	0%	5%	4%	5%
19	**14**	0%	0%	5%	3%	5%
20	**15**	0%	0%	5%	3%	4%
21	**16**	0%	0%	4%	3%	4%
22	**17**	0%	0%	4%	2%	4%
23	**18**	0%	0%	3%	2%	4%
24	**19**	0%	0%	3%	2%	4%
25	**20**	0%	0%	3%	1%	3%
26	**21**	0%	0%	3%	1%	3%
27	**22**	0%	0%	2%	1%	3%
28	**23**	0%	0%	2%	1%	3%
29	**24**	0%	0%	1%	1%	3%

Figure 3-2 Example wall CTS factors

3.2 Load Calculations

This section describes methodologies and assumptions in detail that are used in the load calculation in EBLM. Examples of load calculations are provided in Appendix A.

3.2.1 Solar Radiation

Hourly solar flux on the horizontal surface of the roof is taken from the weather file and used to perform solar radiation calculations. The procedures to calculate normal direct solar radiation and diffuse and reflected radiation for each outdoor surface are the following:

1. Use equations 3-1 to 3-10, the Julian day n, and latitude ϕ to calculate the equation of time (EOT), local solar time (LST), declination angle δ, hour angle w, solar altitude angle α_s, solar zenith angle Θ_z, solar azimuth angle γ_s, and incidence angle Θ.

$$EOT = 229.2(0.000074 + 0.001868cosB - 0.032077sinB$$

$$-0.014615cos2B - 0.04089sin2B) \quad \text{Eqn 3-1}$$

$$B = (n-1)(\frac{360}{365}) \quad \text{Eqn 3-2}$$

$$LST = LCT + EOT = ST + \frac{60}{15}(L_{ST} - L_{LOC}) + EOT \quad \text{Eqn 3-3}$$

Where

LCT = local civil time determined at the longitude of the observer

ST = Standard Time

L_{ST} = standard meridian, degree

L_{LOC} = local meridian, degree

$$\delta = \delta_m \sin(360\frac{284+n}{365}), \quad \text{Eqn 3-4}$$

$$\delta_m = 23.45^0 \quad \text{Eqn 3-5}$$

$$w = \frac{15^0}{h} * t \quad \text{Eqn 3-6}$$

Where

h = 1 hour (to balance units)

t = the number of hours before or after solar noon, - before noon, + after noon

$$\alpha_s = \sin^{-1}(\cos\emptyset \cos\delta \cos w + \sin\emptyset \sin\delta) \qquad \text{Eqn 3-7}$$

$$\theta_z = \cos^{-1}(\cos\emptyset \cos\delta \cos w + \sin\emptyset \sin\delta) \qquad \text{Eqn 3-8}$$

$$\gamma_s = \cos^{-1}(\frac{\sin\alpha_s \sin\emptyset - \sin\delta}{\cos\alpha_s \cos\emptyset}) \qquad \text{Eqn 3-9}$$

$$\theta = \cos^{-1}(\cos\theta_z \cos\beta \cos\theta_z + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma)) \qquad \text{Eqn 3-10}$$

Where

α_s is the solar altitude angle, degree

θ_z is the solar zenith angle, degree

β is a surface tilt from horizontal, and usually used for elevation angle, degree

γ is the surface azimuth clockwise from south, degree

γ_s is the solar azimuth angle clockwise from south, degree

2. Calculate radiation and clearness index

- Instantaneous extraterrestrial irradiation on the horizontal surface of the roof, $G_{O,H}$, W/m^2

$$G_{O,H} = G_{SC}\, e_n \cos\theta_z \qquad \text{Eqn 3-11}$$

Where

e_n is the eccentricity factor, $e_n = 1 + 0.033 * \cos(\frac{360*n}{365})$

$G_{S,C}$ is the solar constant 1367 W/m^2

- Hourly extraterrestrial irradiation on the horizontal surface, $I_{O,H}$, J/m^2

$$I_{O,H} = 3600 * G_{O,H} \qquad \text{Eqn 3-12}$$

- Hourly total radiation on the horizontal surface, $I_{t,H}$, J/m^2

$$I_{t,H} = 3600 * G_{t,H} \qquad \text{Eqn 3-13}$$

Where:

$G_{t,H}$ is the solar flux on horizontal surface, obtained from weather station or database, in W/m^2

- Hourly total radiation clearness index, k_t

$$k_t = \frac{I_{t,H}}{I_{o,H}} \qquad \text{Eqn 3-14}$$

- Hourly diffuse radiation clearness index, k (Chapter 1, Duffie and Beckman 2013)

$$k = 1 - 0.09k_t, \qquad k_t \leq 0.22 \qquad \text{Eqn 3-15}$$

$$k = 0.9511 - 0.1604k_t + 4.388k_t^2 - 16.638k_t^3 + 12.336k_t^4, \qquad 0.22 \leq k_t \leq 0.8 \qquad \text{Eqn 3-16}$$

$$k = 0.165, \qquad k_t > 0.8 \qquad \text{Eqn 3-17}$$

- Hourly diffuse radiation on the horizontal surface, $I_{d,H}$, J/m^2

$$I_{d,H} = k * I_{t,H} \qquad \text{Eqn 3-18}$$

- Instantaneous diffuse radiant flux on the horizontal surface, $G_{d,H}$, W/m^2

$$G_{d,H} = I_{d,H}/3600 \qquad \text{Eqn 3-19}$$

- Hourly direct-beam radiation on the horizontal surface, $I_{b,H}$, J/m^2

$$I_{b,H} = I_{t,H} - I_{d,H} \qquad \text{Eqn 3-20}$$

- Instantaneous direct-beam radiation on the horizontal surface, $G_{b,H}$, W/m^2

$$G_{b,H} = \frac{I_{b,H}}{3600} \qquad \text{Eqn 3-21}$$

3. Convert horizontal radiation to normal radiation
    - Convert horizontal direct-beam radiation to radiation on the tilted (normal) surface, $G_{b,t}$, W/m^2

$$G_{b,t} = G_{b,H} * \frac{\cos(\theta)}{\cos(\theta_z)} \qquad \text{Eqn 3-22}$$

- Convert horizontal diffuse radiation to radiation on the vertical surface, $G_{d,v}$, W/m^2

$$G_{d,v} = G_{d,H} * (\frac{1+\cos(\beta)}{2}) \quad \text{Eqn 3-23}$$

- Convert horizontal ground reflected radiation to radiation on the tilted surface, $G_{g,t}$, W/m^2

$$G_{g,t} = G_{t,H} * \left(\frac{1-\cos\beta}{2}\right) * \rho_g \quad \text{Eqn 3-24}$$

Where

ρ_g is the ground reflectance with respect to solar radiation

The methodologies of solar calculation are discussed. In the next two sections, the methods of CTS and RTS will be discussed in detail.

3.2.2 Conduction Time Series Method

The CTS and RTS calculations are used to account for two time-delay effects in the heat transfer processes:

- *Delay of conductive heat gain through opaque massive exterior surfaces*
- *Delay in the conversion of radiative heat gain to cooling load within the building*

Heat transfer through the wall and roof is due to the temperature difference between outdoor and indoor air as well as solar-heating of the outdoor surface. Some of this heat transfer becomes heat gain at the indoor surface – sometime later and this process is mimicked by the CTS calculation. Subsequently, the radiant portion of this heat gain becomes cooling load and the delay associated with the process is mimicked by the RTS calculation.

The CTS procedure is defined by equations 3-25 to 2-27:

$$q_{i,\theta-n} = UA(T_{e,\theta-n} - T_{rc}) \quad \text{Eqn 3-25}$$

Where

$q_{i,\theta-n}$= conductive heat gain caused by $T_{e,\theta-n}$, W

U = overall heat transfer coefficient for surface, W/(m^{2}K)

A = surface area, m^2

$T_{e,\theta-n}$= sol-air temperature n hours ago

T_{rc} = presumed constant room air temperature, ℃

The sol-air temperature, t_e, is the equivalent outdoor air temperature that is the result of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings and convective heat exchange with outdoor air (Chapter 18, ASHRAE 2013). It is calculated using equation 3-26.

$$T_e = T_{out} + \frac{\alpha E_t}{h_0} - \frac{\varepsilon \Delta R}{h_0} \quad \text{Eqn 3-26}$$

Where

T_e is the sol-air temperature, ℃

T_{out} is the outdoor air temperature, ℃

α is the solar absorptance of outdoor surface

E_t is total solar radiation incident on surface, W/(m^{2}K)

h_0 is the outdoor convective heat transfer coefficient, taken as h_0 = 17 W/(m^{2}K) to represent forced convection

$\varepsilon \Delta R / h_0$ = 4 K for horizontal surfaces (Bliss 1961)

$\varepsilon \Delta R / h_0$ = 0 for vertical surfaces (Bliss 1961)

Conductive heat gain through walls or roof can be estimated using conductive heat input for the current hour and past 23 hours as shown below:

$$q_\theta = c_0 q_{i,\theta} + c_1 q_{\theta-1} + c_2 q_{\theta-2} + c_3 q_{\theta-3} + \cdots + c_{23} q_{\theta-23} \quad \text{Eqn 3-27}$$

Where

q_θ = current indoor conductive heat gain at the indoor surface, W (θ denotes time in this context)

c_0, c_0, etc = conduction time factor (CTS factor) as specified in Section 3.1.6

3.2.3 Radiant Time Series Method

The radiant portion of heat gain from equipment (i.e. lighting, plugs, working equipment), occupancy, and direct solar transmission is also converted to cooling load after a delay caused by the thermal mass of the building and contents.

The procedure for calculating cooling for each load component with the RTS method is described in the ASHRAE Handbook of Fundamentals (Chapter 18, ASHRAE 2013):

1. Calculate 24-hours profile of component heat gains by equation 3-25 for each wall and/or roof (i.e. 24 values of q_θ).
2. Split heat gains into radiant and convective parts from a source of heat gain.
3. Apply RTS factors to radiant part of heat gains to account for time delay. See equation 3-28.
4. Sum up all cooling load components to obtain the total hourly cooling load of the building to determine the peak load for a day or a month.

$$q_r = r_0 q_{i,r} + r_1 q_{r-1} + r_2 q_{r-2} + r_3 q_{r-3} + \cdots + r_{23} q_{r-23} \quad \text{Eqn 3-28}$$

Where

q_r = current heat gain accounting for delay effect, W (subscript r denotes time in this context)

r_0, r_1, etc = radiant time factor (RTS factor) as specified in Section 3.1.6

The next section describes the methods that are used to calculate the load due to windows.

3.2.4 Load due to Windows

The window calculations consist of three parts: conductive heat transfer through windows, direct solar transmission, and absorbed/redirected solar heat gain through windows.

1. Equation 3-29 is used to calculate the conductive heat transfer through windows. $q_{win,c}$ is split into delayed (radiant) cooling load and immediate (convective) cooling load calculated by equations 3-30 and 3-31. The RTS method described in section 3.2.3 is used to account for the delayed cooling load.

$$\dot{q_{win,c}} = U_{Win} * A_{tot} * (T_{out} - T_{in}) \qquad \text{Eqn 3-29}$$

Where

$\dot{q_{win,c}}$ = heat transfer (i.e. heat gain) through windows, W

U_{Win} = total window U-value, W/m^2°C

A_{tot} = total window area including areas of center glass, edge glass, and frame, m^2

T_{out} = outdoor air temperature, °C

T_{in} = indoor air temperature, °C

$$\dot{q_{win,c,delayed}} = (F_r) * \dot{q_{win,c}} \qquad \text{Eqn 3-30}$$

$$\dot{q_{win,c,immediate}} = (1 - F_r) * \dot{q_{win,c}} \qquad \text{Eqn 3-31}$$

Where

$q_{win,c,delayed}$ is the delayed cooling load, W

$q_{win,c,immediate}$ is the immediate cooling load, W

F_r is the fraction radiant, taken as F_r = 0.6 in all cases considered in this thesis

2. Equation 3-35 is used to calculate heat gain caused by solar transmission with the solar transmittance is calculated by equations 3-32 to 3-34. Solar gain through the frame area is generally small and thus neglected in the window solar calculation (Wright 1995). The CTS method is not used for the window calculation because the thermal capacity of glazing is small. All of the direct transmission is radiant gain, which is the delayed cooling load, and the RTS method (solar RTS factors) is used to account for this delay.

$$\tau(\theta) \cong \tau(\theta = 0) * \cos^{0.4}(\theta) \qquad \text{Eqn 3-32}$$

$$\tau_{cg} = \frac{G_{b,t} * \tau(\theta) + G_d * \tau(\theta = 60)}{G_{b,t} + G_d} \qquad \text{Eqn 3-33}$$

$$\tau_{sol} = \tau_{cg} * \left(\frac{A_{view}}{A_{win}}\right) \qquad \text{Eqn 3-34}$$

$$\dot{q_{win,s}} = A_{win} * \tau_{sol} * (G_{b,t} + G_d) \qquad \text{Eqn 3-35}$$

Where

$\tau(\theta)$ is the centre-glass solar transmittance at incident angle θ

τ_{cg} is the solar transmittance of the centre-glass

G_d is the sum of the sky diffuse and ground reflected solar radiation, W/m^2

A_{view} is the view area of the window, m^2

A_{win} is the total window area, m^2

τ_{sol} is the solar transmittance of the window

$q_{win,s}$ is the direct solar transmission heat gain through windows, W

3. Absorbed/redirected heat gain is the last component of the window calculation, and is calculated using equations 3-36 to 3-39. The heat gain is split into radiant

(delayed) cooling load and convective (immediate) cooling load as shown in equations 3-40 and 3-41. The RTS method is then used to account for the delay as radiant heat gain is converted to cooling load.

$$SHGC(\theta) \cong SHGC(\theta = 0) * \cos^{0.4}\theta \quad \text{Eqn 3-36}$$

$$SHGC_{cg} = \frac{G_{b,t} * SHGC(\theta) + G_d * SHGC(\theta = 60)}{G_{b,t} + G_d} \quad \text{Eqn 3-37}$$

$$SHGC_{product} = SHGC_{cg} * \left(\frac{A_{view}}{A_{win}}\right) \quad \text{Eqn 3-38}$$

$$\dot{q}_{win,ar} = A_{win} * (SHGC_{product} - \tau_{sol}) * (G_{b,t} + G_d) \quad \text{Eqn 3-39}$$

Where

$SHGC(\theta)$ is the centre-glass solar heat gain coefficient at θ

$SHGC_{cg}$ is the solar heat gain coefficient of the centre-glass area

$SHGC_{product}$ is the solar heat gain coefficient of the window

$q_{win,ar}$ is the absorbed/redirected solar gain, W

$$\dot{q}_{win,ar,delayed} = (F_r) * \dot{q}_{win,ar} \quad \text{Eqn 3-40}$$

$$\dot{q}_{win,ar,immediate} = (1 - F_r) * \dot{q}_{win,ar} \quad \text{Eqn 3-41}$$

Where

$q_{win,ar,delayed}$ is the delayed cooling load, W

$q_{win,ar,immediate}$ is the immediate cooling load, W

The methods of calculating shading systems (fixed and operable) are address in the next section.

3.2.5 Shading

ASHRAE recommends a simplified methodology to calculate the energy impact of a fixed shading system. The first step calculates the profile angle `Ω, defined as the angular difference between a horizontal plane and a plane tilted about a horizontal axis in the plane of the fenestration until it includes the sun (Chapter 15, ASHRAE 2013). The profile angle can be calculated by equation 3-41:

$$`\Omega = \tan^{-1}\frac{\tan\alpha_s}{\cos(\gamma_s-\gamma)} \qquad \text{Eqn 3-42}$$

Where:

α_s is the solar altitude angle

$\gamma_s - \gamma$ is surface solar azimuth angle

The second step calculates the IAC (Θ, `Ω) for direct beam radiation (slat type shading only), SHGC values for direct beam ($SHGC_{shaded,b}$) and diffuse plus reflected radiation ($SHGC_{shaded,d,r}$), and the solar transmittance values for direct beam ($\tau_{shaded,b}$) and diffuse plus reflected ($\tau_{shaded,d,r}$). The IAC (Θ, `Ω) and shaded SHGC values are calculated using equations 3-43 to 3-45 (Chapter 15, ASHRAE 2013).

$$IAC\ (\theta,`\Omega) = IAC_0 + (IAC_{60} - IAC_0) * \min(1{,}0.02 * `\Omega) \qquad \text{Eqn 3-43}$$

$$SHGC_{shaded,b} = IAC\ (\theta,`\Omega) * SHGC(\theta)_b \qquad \text{Eqn 3-44}$$

$$SHGC_{shaded,d,r} = IAC_{diff} * SHGC(\theta = 60)_{d,r} \qquad \text{Eqn 3-45}$$

Where

IAC (Θ, `Ω) is the ratio $SHGC_{shaded}/SHGC_{unshaded}$ at the incidence angle Θ and profile angle `Ω.

IAC_0 is IAC at normal incidence.

IAC_{60} is IAC at profile angle of 60 degree.

IAC_{diff} is IAC with respect to diffuse insolation.

$SHGC_{shaded,b}$ is the shaded solar heat gain coefficient of direct bean radiation.

$SHGC_{shaded,d,r}$ is the shaded solar heat gain coefficient of sky diffuse and ground reflected radiation.

Since IAC values of drapery, roller shades, and insect screens are not strongly influenced by the incidence angle, constant IAC values are used (Chapter 15, ASHRAE 2013). Shaded SHGC values of drapery, roller shades, and insect screen for direct beam, diffuse and reflected radiation are also calculated using equations 3-44 and 3-45. Values of IAC_0, IAC_{60}, and IAC_{diff} can be obtained from Chapter 15 of the ASHRAE Handbook of Fundamentals.

The shaded solar transmittances can be estimated using equations 3-46 and 3-47. This approach should be recognized as approximate because the IAC is intended to apply to SHGC, not directly to solar transmittance. Nevertheless, by using IAC in combination with τ_{sol} it is possible to resolve the absorbed/redirected portion of solar gain for shaded windows, and the corresponding radiant/convective split, without lumping longwave radiant gain with direct solar transmission. This maneuver also provides computational efficiency.

$$\tau_{shaded,b} = IAC\ (\theta, \grave{}\Omega) * \tau(\theta)_b \qquad \text{Eqn 3-46}$$

$$\tau_{shaded,d,r} = IAC_{diff} * \tau(\theta = 60)_{d,r} \qquad \text{Eqn 3-47}$$

The final step calculates the solar gain through windows. Repeat step 2 and 3 from Section 3.2.4 using shaded SHGCs ($SHGC_{shaded,b}$ and $SHGC_{shaded,d,r}$) and τ ($\tau_{shaded,b}$ and $\tau_{shaded,d,r}$) instead of SHGC (Θ), SHGC (Θ=60), τ (Θ) and τ (Θ=60).

Additional steps are required to calculate the performance of the operable shading system options. For these calculations, the corresponding values for IAC_0, IAC_{60}, and IAC_{diff} are selected according to user input. For example, if the outdoor temperature control strategy is selected, the model checks the outdoor temperature. When the outdoor temperature is within the specified limit, the model will select values of *IAC_0 when open*, *IAC_{60} when open*, and *IAC_{diff} when open* for the operable shading calculation, otherwise values of *IAC_0 when closed*, *IAC_{60} when closed*, and *IAC_{diff} when closed* will be selected.

A simplification is made for the outdoor operable shading system. The shading system will be retracted when shading is not required (IAC (ϴ, Ὼ) is set to unity), otherwise the slat angle is set to zero, (fully close, IAC (ϴ, Ὼ) =0), so that beam radiation flux is fully blocked but some small amount of the diffuse component is transmitted. Both SHGC and τ_{sol} are then modified in a similar fashion.

The methods of calculation the fenestration system including the shading system have discussed in detail. The remaining calculations of the building enclosure are: walls and roof, which will be discussed in the later sections.

3.2.6 Wall

The steps for calculating the space load caused by walls are:

1. Calculate the sol-air temperature using equation 3-26. The sol-air temperature is equal to the outdoor temperature in the absence of solar radiation and clear-sky cooling.
2. Calculate the heat transfer through the walls using equation 3-25, and generate a 24-hour profile of heat gain. Apply the CTS method to account for the thermal

storage effect of the walls using equation 3-27. During the hours of heat loss through walls, negative signs are assigned to the heat gain values.

3. Split the heat gain into convective and radiative portions ($F_r = 0.6$).
4. Apply the RTS method to the radiative portion of heat gain to calculate the corresponding cooling load using equation 3-28.
5. Sum the cooling loads caused by the two components of heat gain to obtain the total cooling load from the walls.

3.2.7 Roof

The procedure for calculating the space load caused by the roof is similar to that for walls:

1. Calculate the sol-air temperature using equation 3-26. The solar flux E_t is the solar flux on the horizontal surface.
2. Calculate the heat transfer through the roof using equation 3-25, and generate 24-hour profile of heat gain. Apply the CTS method to account for the thermal storage effect of the roof using equation 3-27.
3. Split the heat gain into convective and radiative portions ($F_r = 0.6$).
4. Apply the RTS method to the radiative portion of heat gain to calculate the corresponding cooling load using equation 3-28.
5. Sum the two cooling load components to obtain the total cooling load from the roof.

3.2.8 Slab and Below Grade Walls

The heat transfer through the slab is neglected in the load calculation because the total heat transfer through the slab is a small portion of the total heat transfer for medium-sized or large commercial buildings.

3.2.9 Internal Heat Gain

Predicting internal heat gains can be difficult because the number of occupants, and hours of equipment usage varies across the day. The load calculation uses the estimated schedules to predict the hours of operation of lighting, plug loads, ventilation, and air leakage.

3.2.9.1 Lighting and Plug Load

The followings steps are used to calculate the lighting and plug loads:

1. Calculate the heat gain of lighting and plug loads per hour using equations 3-48 and 3-49.

$$q_{lighting} = LPD * A_{floor} \qquad \text{Eqn 3-48}$$

$$q_{plug\ load} = PD * A_{floor} \qquad \text{Eqn 3-49}$$

Where

$q_{lighting}$ is the heat generated by lighting, W

$q_{plug\ load}$ is the heat generated by plug load, W

LPD is the lighting power density, W/m^2

A_{floor} is the total exterior floor area, m^2

PD is the plug load power density, W/m^2

2. Split the heat gain into convective and radiative portions using the radiant fractions listed on Tables 3-4 and 3-5.
3. Apply the RTS method to the radiative portion of heat gain to calculate the corresponding cooling load using equation 3-28.
4. Sum the two component cooling loads to calculate the total cooling load from lighting plus plug loads.

3.2.9.2 Occupants

The human body generates latent and sensible heat. Latent heat is associated with moisture that must be removed by the air conditioner or ventilation. Sensible heat gain is broken down into convective and radiative portions. The typical fractions of convective and radiant heat gain are 40% and 60%, respectively (Chapter 18, ASHRAE 2013). The steps of calculating the occupant load are followings:

1. Split the sensible heat gain into convective and radiative portions as described on Table 3-3.
2. Apply the RTS method for the radiative portion to calculate the corresponding cooling load using equation 3-28.
3. Sum the latent heat gain, convective heat gain and cooling load associated with radiant heat gain to obtain the total cooling load from the occupants.

3.2.10 Ventilation and Air Leakage

Equation 3-49 is used to calculate the required ventilation flow rate (L/s). The flow rate to the building will be changed according to the ventilation schedule as well as the number of people. Equation 3-50 is applied to calculate the ventilation load.

$$Q_v = (R_p n_p + R_a A_{floor})/E_z \quad \text{Eqn 3-49}$$

Where:

R_p is outdoor air rate per person in L/s-person

n_p is the number of people

R_a is the outdoor air rate per unit floor area in L/s-m^2

A_{floor} is the total exterior floor area in m^2

E_z is the zone air distribution effectiveness, ranging from 0.5 to 1.2

$$q_s = 1.21 * Q_v * (T_{out} - T_{in}) \quad \text{Eqn 3-50}$$

Where:

1.21 has an unit of $\frac{W}{\frac{L}{s} * ℃}$

q_s is the sensible heat load in W

Q_v is the required ventilation rate in L/s

T_{out} is the outdoor air temperature in ℃

T_{in} is the indoor air temperature in ℃

The air leakage flow rate is estimated using the Air-Change method (Chapter 6, McQuiston 2005).

$$Q_{al} = (ACH) * V/C_T \quad \text{Eqn 3-51}$$

Where

Q_{al} is the infiltration rate, m^3/s

ACH is the number of air changes per hour, hr^{-1} in service

V is the gross space volume, m^3

C_T is a constant, 3600 for SI units

The load calculation model adjusts the air leakage by the wind speed. The wind speed adjustment factor is used to account for the pressure coefficients of the building, which influence the infiltration rate (Gowri 2009), and is estimated by equation 3-52:

$$WSF = (\frac{average(ws)}{10})^2 \qquad \text{Eqn 3-52}$$

Where

$average(ws)$ is the average of the annual wind speed, km/h

The sensible heat gain associated with air leakage, $q_{al,s}$, is calculated by equation 3-53:

$$q_{al,s} = WSF * \frac{Q_{al} * C_p * (T_{in} - T_{out})}{v_o} \qquad \text{Eqn 3-53}$$

Where

C_P is the specific heat of the indoor air, 1000 J/(kg-C)

v_o is the specific volume of indoor air, 0.83 m^3/kg

T_{in} is the indoor air temperature, ℃

T_{out} is the outdoor air temperature, ℃

The latent component of heat gain is not accounted for in the ventilation and air leakage calculation because humidity ratios of indoor and outdoor are assumed to be equal. More detail could be added for future improvement.

4.0 Comparison

Before any model is used for engineering decision making, some validation and/or comparisons with measured data or established software is needed. To accomplish this, identical building specifications were entered into EBLM and eQUEST to validate the accuracy and functionality of EBLM.

eQUEST is a free building energy-use analysis tool. The equations and algorithms used in eQUEST are based on the Engineers Manual DOE-2, which provides the user with significant detail (DOE-2 1982). eQUEST allows users to perform detailed analysis of state-of-the-art building design technologies using sophisticated building energy simulation techniques (DOE-2 1982).

A number of points are worth noting:

- Weather data was extracted from the eQUEST weather profile, and used directly in EBLM
- eQUEST allows users to define the building enclosure by selecting layers of wall and roof or by entering single overall U-values. EBLM building enclosures were defined by specifying single overall U-values rather than selecting layers for the sake of simplicity. In this comparison, eQUESt defines the building enclosure by entering single overall U-values.

4.1 Building Specifications

A representative commercial building was chosen to compare. The building model has 3-storeys (each floor is considered as one zone). It oriented due north (with a rectangular shape as shown in Figure 4-1 to 4-4). Several simplifications have been made for the building model:

- Brick walls, concrete roof (high R-value), and medium weight floors with carpet were used for the structure of the building model to account for the thermal storage effects.
- Schedules of lighting, plug loads, occupancy, and ventilation were set from 7 AM to 8 PM, and no holiday schedules were defined for either model.
- No core and perimeter zones were defined.
- No heat transfer between the ground and the building was considered.

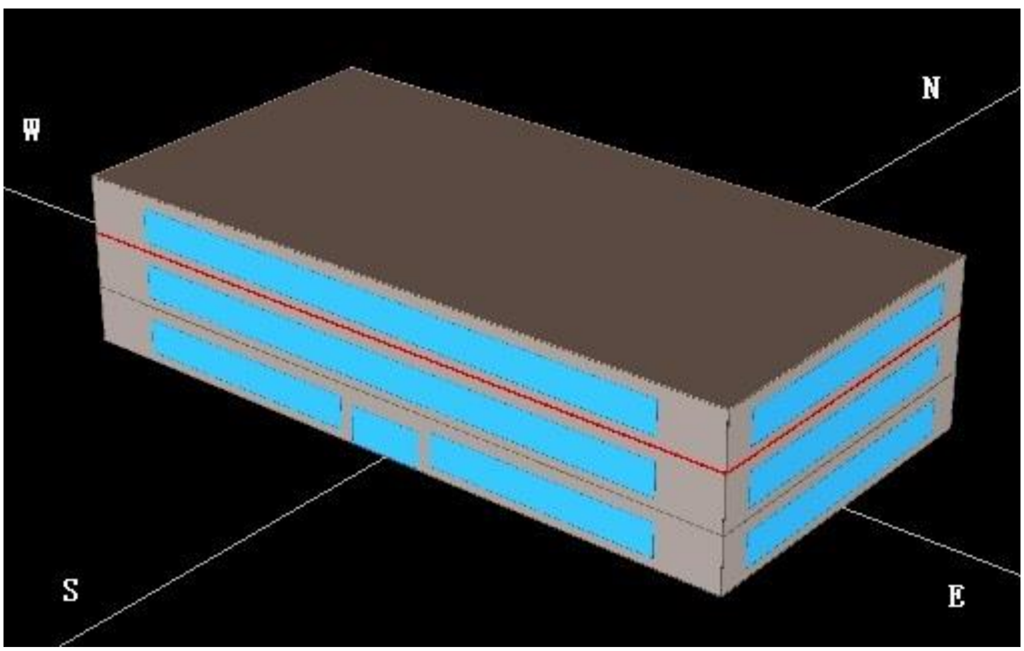


Figure 4-1 3-D view of the building model

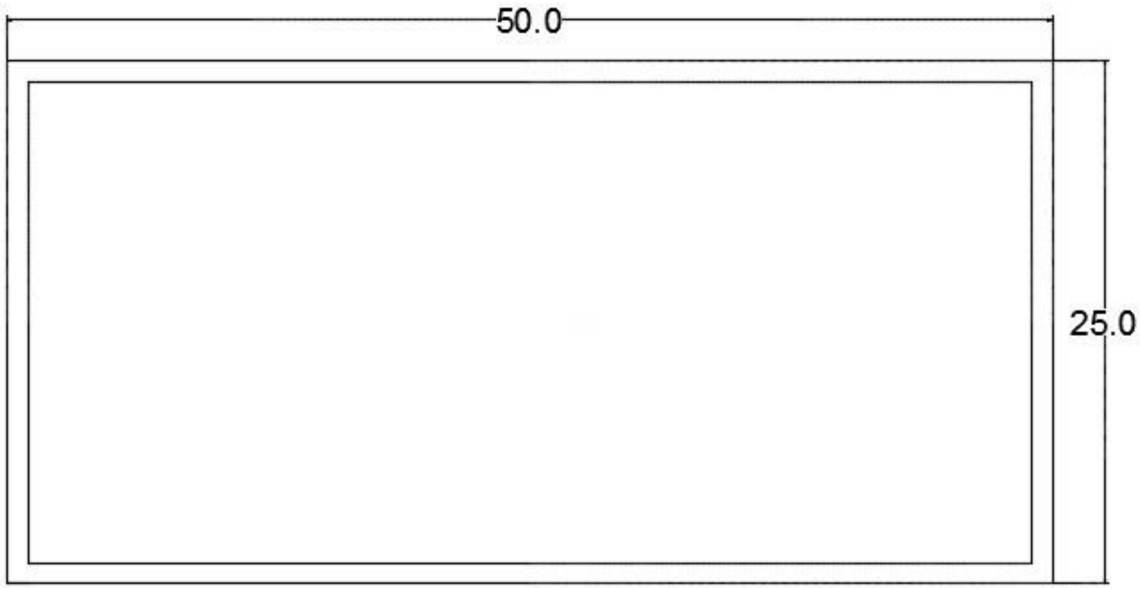


Figure 4-2 Exterior dimensions of the floor area (not-to-scale)

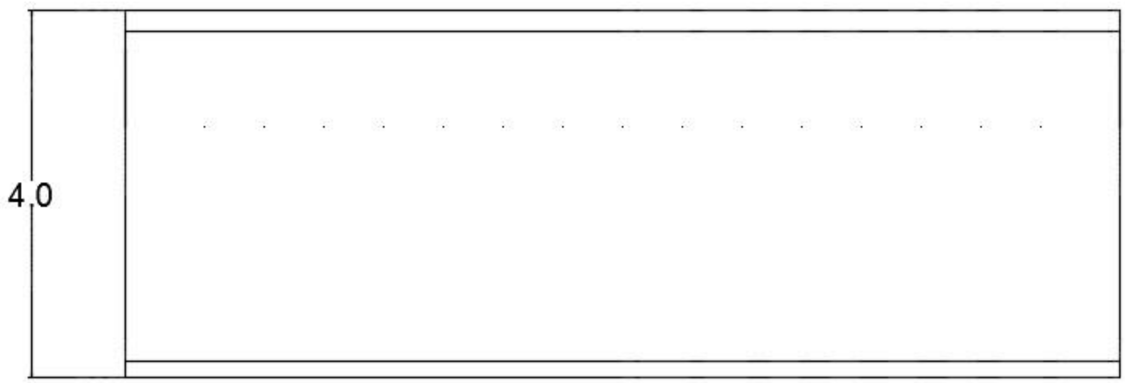


Figure 4-3 4 m is the floor-to-floor height, (not-to-scale)

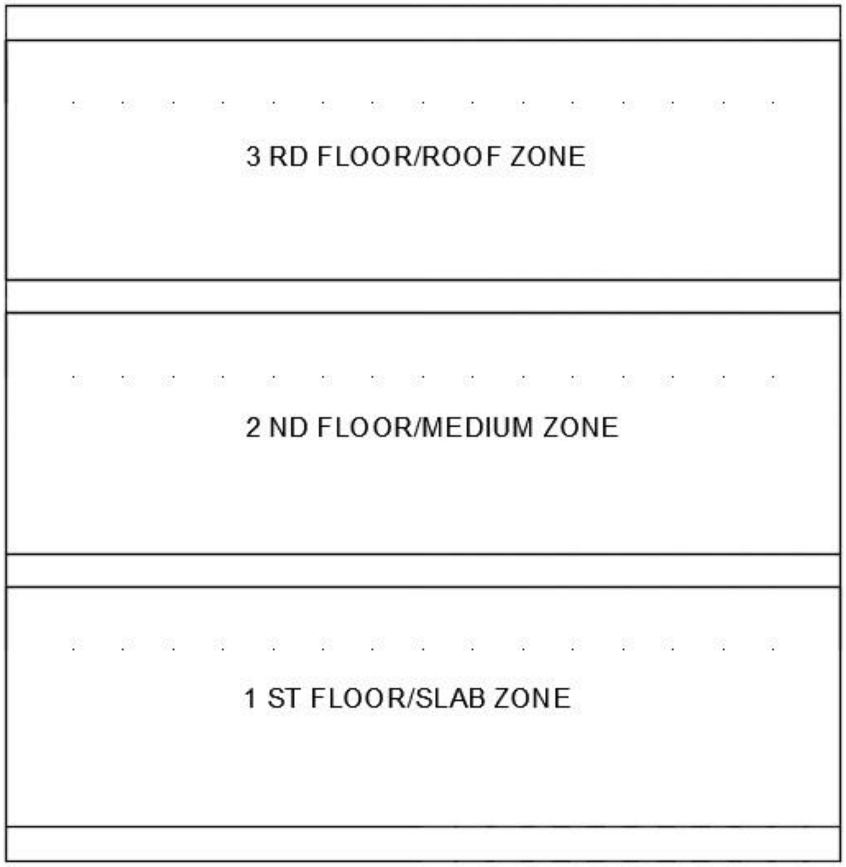


Figure 4-4 Building zone orientations (vertical cross section, not-to-scale)

The following Tables 4-1 to 4-5 show specifications of the building model to validate EBLM with eQUEST. The specifications of the eQUEST model are shown in Appendix B.

Table 4-1 Building Parameters for comparison

Item	Value	Unit
Location	Toronto, Canada	
Latitude	43.6	Deg. N
Longitude	79.4	Deg. W
Year	2012	
Ground solar reflectance	0.2	
Length of building	50	m
Width of building	25	m
Floor-to-floor height	4	m
Number of floors	3	
WWR	0.5	
Orientation of wall	Vertical	
Orientation of roof	Horizontal	
Radiative fraction of walls and roof	0.6	
Effective R-Value of wall	16.5	ft^2F/Btu
Effective R-Value of roof	21	ft^2F/Btu
$SHGC_{cg,b}(\theta=0)$	0.65	
U-value of window	0.3	Btu/ft^2F

Table 4-2 Ventilation and air leakage information

Ventilation Rate at night Schedule (L/s)	83.3
Air leakage (ACH)	0.08
Occupancy Category	Office Space
People Outdoor Air Rate (cfm/person)	5
Area Outdoor Air Rate (cfm/ft^2)	0.06

Table 4-3 Occupancy information

Radiative Fraction	0.6
Number of Occupants	135
Sensible Portion (W)	70
Latent Portion (W)	45
Heat Generated per Occupant(W)	115
Occupancy Schedule	7 AM to 8 PM

Table 4-4 Plug load information

Radiative Fraction	0.4
Plug Loads (W/m2)	9
Plug Loads Schedule	7 AM to 8 PM

Table 4-5 Lighting fixture information

Radiative Fraction	0.48
Lighting Power Density (W/m2)	9.7
Lighting Schedule	7 AM to 8 PM

4.2 Validation of Building Load Components

The monthly loads for each building load component in EBLM and eQUEST models were compared. Some results agreed well but others differed more significantly. Monthly and annual building load components are discussed below.

4.2.1 Solar Gain – Windows

Table 4-6 shows a comparison of the calculated values for window solar heat gain from the eQUEST and EBLM models. Differences are generally between 1% and 16%, but the percentage differences of April, June, August, and November are higher than other months. There are two possible reasons that cause the difference. The first is the ground reflectance. The option to enter the ground reflectance is not available in eQUEST;

therefore, the method by which eQUEST models ground reflected solar radiation is unknown. EBLM uses a constant value of 0.2 for ground reflectance through the year. The other reason is the method by which insolation is estimated. Both EBLM and eQUEST convert the total horizontal radiation from the weather data to calculate the direct beam, sky diffuse, and ground reflected radiation on vertical surfaces. However EBLM and eQUEST use different methods to calculate solar flux on vertical surfaces (DOE-2 1982).

Table 4-6 Window solar heat gain comparison results

Solar Gain Windows	eQUEST		EBLM	Difference (%)	Absolute Difference (MWh)
Month	Total Gain (MBtu)	Total Gain (MWh)	Total Gain (MWh)		
January	53.7	15.7	15.6	1%	0.14
February	60.1	17.6	16.6	5%	0.97
March	75.1	22.0	20.8	5%	1.18
April	81.1	23.8	21.3	10%	2.44
May	94.0	27.5	26.3	4%	1.24
June	96.1	28.2	24.9	12%	3.28
July	97.3	28.5	27.3	4%	1.16
August	97.3	28.5	23.9	16%	4.55
September	88.4	25.9	24.3	6%	1.56
October	71.3	20.9	20.1	4%	0.77
November	39.0	11.4	9.8	14%	1.60
December	38.8	11.4	10.9	5%	0.52
Total	892	261	242	7%	19.4

4.2.3 Conduction – Windows

Table 4-7 shows the calculated loads of window conduction. The monthly percentage difference is uniformly about 10% except in those months (July, and August) when the conduction load is especially small. Values applied for the surface film coefficient and wind speed could be possible reasons for the difference. eQUEST calculates the conduction through glazing unit and frame separately, accounting for effects of surface film coefficient and wind speed. EBLM takes the advantage of calculating the window conduction by a single overall U-value (including glazing unit and frame). This type of window specification is easier for early stage design, and U-value data is provided by the most manufactures in this form.

Table 4-7 Window conduction comparison results

Conduction Windows	eQUEST		EBLM	Difference (%)	Absolute Difference (MWh)
Month	Total Transfer (MBtu)	Total Transfer (MWh)	Total Transfer (MWh)		
January	-84.8	-24.8	-27.7	-11%	2.83
February	-76.9	-22.5	-24.9	-10%	2.34
March	-70.6	-20.7	-22.6	-9%	1.86
April	-49.4	-14.5	-15.7	-8%	1.23
May	-32.4	-9.5	-10.0	-5%	0.50
June	-14.2	-4.2	-4.1	0%	-0.01
July	-5.2	-1.5	-1.2	-29%	-0.34
August	-8.6	-2.5	-2.1	-18%	-0.39
September	-21.8	-6.4	-6.7	-5%	0.34
October	-42.4	-12.4	-13.5	-8%	1.03
November	-55.2	-16.2	-17.8	-10%	1.64
December	-75.5	-22.1	-24.3	-10%	2.18
Total	-537	-157	-170	-8%	13.2

4.2.4 Walls

Table 4-8 shows the wall conduction loads. In general, the monthly percentage difference is between 2% and 8%, although large percent differences are observed in months when the load is small (i.e., with shoulder seasons when the load switches between heating and cooling). The absolute difference is consistently low. Two possible reasons can be used to explain these differences. The first one may be the method of calculating thermal storage effect (delayed cooling load effect). EBLM employs CTS and RTS methods (Chapter 18, ASHRAE 2013) that accounts for the previous 24 hours heat gain. The weighting factors of CTS and RTS for walls are based on the R-value and the structure of the building enclosure. eQUEST generates the weighting factors based on user input about the building, and accounts for only the previous 4 hours heat gain. The other possible cause is the sol-air temperature calculation associated with outdoor surface film coefficient. EBLM uses a recommended value of 17 W/(m^2 K) for outdoor surface film coefficient (Chapter 18, ASHRAE 2013). In reality, this value varies with wind speed, surface roughness, and surface temperature. According to DOE-2, eQUEST calculates the outdoor surface film coefficient based on the wind speed, solar radiation, and surface roughness. eQUEST uses the following equation to calculate the outdoor surface film coefficient (DOE-2, 1982).

$$h_o = A + (B * V) + (C * V^2) \qquad \text{Eqn 4-1}$$

Where:

h_o is the surface film coefficient, $W/m^2 ℃$

V is the wind speed, m/s

A, B, C are coefficients list in Table 4-9

Consider a brick wall with a low wind speed of 2 m/s, equation 4-1 gives h_0= 21.9 W/m^2°C. For a wind speed of 6 m/s, the equation 4-1 gives h_o = 42 W/m^2°C. Some discrepancy between EBLM and eQUEST may arise simply because the h_o value used by eQUEST are consistently higher than 17 W/m^2°C. Accordingly, Table 4-8 shows that eQUEST produces wall conduction heat gain values that are consistently lower than the corresponding EBLM results, in months of appreciable heat gain, as might be expected.

Table 4-8 Wall comparison results (including sol-air effect)

Heat Transfer through Walls	eQUEST		EBLM	Difference (%)	Absolute Difference (MWh)
Month	Total Heat Transfer (MBtu)	Total Heat Transfer (MWh)	Total Heat Transfer (MWh)		
January	-19.3	-5.6	-5.8	-2%	0.11
February	-16.5	-4.8	-5.0	-3%	0.13
March	-13.9	-4.1	-4.2	-2%	0.08
April	-8.8	-2.6	-2.5	-2%	-0.06
May	-3.5	-1.0	-0.9	-17%	-0.15
June	1.6	0.5	0.5	8%	-0.04
July	4.2	1.2	1.3	3%	-0.03
August	4.0	1.2	0.9	26%	0.31
September	-0.2	-0.1	-0.3	-297%	0.22
October	-6.7	-2.0	-2.1	-7%	0.13
November	-11.4	-3.3	-3.6	-8%	0.26
December	-17.0	-5.0	-5.1	-3%	0.16
Total	-87.5	-25.6	-26.8	-4%	1.1

Table 4-9 DOE-2 coefficients for surface film coefficient calculation (DOE-2, 1982)

Surface Roughness	A	B	C
Stucco	11.58	6.796	0
Brick and rough plaster	12.49	4.687	0.0378
Concrete	10.79	4.827	0
Clear pine	8.23	4.611	-0.0755
Smooth plaster	10.22	3.569	0
Glass, white paint on pine	8.23	3.836	-0.0472

4.2.5 Roof

Table 4-10 shows calculated roof conduction loads. The monthly percentage difference between eQUEST and EBLM for the roof is higher than the percentage difference for walls, especially in the summer time, although the absolute difference is consistently low. The method of calculating the roof conduction is similar to the method of calculating wall conduction. As a consequence, the surface film coefficient is likely causing the difference. Again, the eQUEST results are consistently smaller than the EBLM results for months of appreciable heat gain.

Table 4-10 Roof comparison results (including sol-air effect)

Heat Transfer through Roof	eQUEST		EBLM	Difference (%)	Absolute Difference (MWh)
Month	**Total Heat Transfer (MBtu)**	**Total Heat Transfer (MWh)**	**Total Heat Transfer (MWh)**		
January	-23.2	-6.8	-7.7	-13%	0.87
February	-20.4	-6.0	-6.6	-11%	0.66
March	-17.8	-5.2	-5.8	-12%	0.62
April	-11.9	-3.5	-3.8	-11%	0.37
May	-6.3	-1.9	-2.1	-12%	0.22
June	-0.9	-0.3	-0.4	-58%	0.15
July	1.9	0.6	0.3	41%	0.23
August	1.3	0.4	-0.1	135%	0.50
September	-3.7	-1.1	-1.6	-45%	0.48
October	-10.4	-3.0	-3.7	-21%	0.63
November	-14.4	-4.2	-5.1	-21%	0.87
December	-20.3	-5.9	-6.9	-15%	0.91
Total	-126	-37	-43	-18%	6.5

4.2.6 Occupants

Table 4-11 shows the occupancy loads. Sensible and latent loads are combined into a single load for comparison. The monthly percentage difference is low and relatively uniform through the year. The difference is higher in summer months. eQUEST does not provide an option to enter heat gains per person (W/person) as well as information on how to split the sensible and latent portions of heat gain. The only option to enter the number of occupant is design maximum density (ft^2/person). EBLM uses a recommended sensible and latent split (0.6 and 0.4, respectively) as well as the heat generated per occupant (115 W/person, office space) from the ASHRAE Handbook of Fundamentals (Chapter 18, ASHRAE 2013).

Table 4-11 Occupancy comparison results

Occupants	eQUEST		EBLM	Difference (%)	Absolute Difference (kWh)
Month	Gain (MBtu)	Gain (kWh)	Gain (kWh)		
January	23.1	6.8	6.7	0%	0.0
February	21.0	6.2	6.1	1%	0.1
March	23.7	6.9	6.7	3%	0.2
April	23.0	6.8	6.5	3%	0.2
May	23.8	7.0	6.7	4%	0.2
June	23.1	6.8	6.5	4%	0.2
July	23.8	7.0	6.7	4%	0.2
August	23.8	7.0	6.7	4%	0.2
September	23.1	6.8	6.5	4%	0.2
October	23.8	7.0	6.7	3%	0.2
November	23.0	6.7	6.5	3%	0.2
December	23.3	6.8	6.7	1%	0.1
Total	278	81.6	79.3	3%	2.3

4.2.7 Lighting

Table 4-12 shows the lighting loads. Results are identical. The load calculation model uses the floor area based on exterior dimensions.

Table 4-12 Lighting comparison results

Lighting	eQUEST	EBLM	Difference (%)	Absolute Difference (MWh)
Month	Total Heat Gain (MWh)	Total Heat Gain (MWh)		
January	15.8	15.8	0%	0
February	14.3	14.3	0%	0
March	15.8	15.8	0%	0
April	15.3	15.3	0%	0
May	15.8	15.8	0%	0
June	15.3	15.3	0%	0
July	15.8	15.8	0%	0
August	15.8	15.8	0%	0
September	15.3	15.3	0%	0
October	15.8	15.8	0%	0
November	15.3	15.3	0%	0
December	15.8	15.8	0%	0
Total	186	186	0%	0

4.2.9 Plug Load

Table 4-13 shows the plug loads. The monthly percentage difference has a constant value of 7% throughout the year. The plug load for EBLM is 7% higher than eQUEST. eQUEST states that part of the heat generated from equipment goes into the space within walls (exterior) and roof, and is transferred out of the building. This heat loss through the enclosure may be the cause of this difference.

Table 4-13 Plug load comparison results

Plug Load	eQUEST	EBLM	Difference (%)	Absolute Difference (MWh)
Month	**Total Heat Gain (MWh)**	**Total Heat Gain (MWh)**		
January	13.6	14.6	7%	-1.1
February	12.3	13.2	7%	-1.0
March	13.6	14.6	7%	-1.1
April	13.2	14.2	7%	-1.0
May	13.6	14.6	7%	-1.1
June	13.2	14.2	7%	-1.0
July	13.6	14.6	7%	-1.1
August	13.6	14.6	7%	-1.1
September	13.2	14.2	7%	-1.0
October	13.6	14.6	7%	-1.1
November	13.2	14.2	7%	-1.0
December	13.6	14.6	7%	-1.1
Total	160	172	7%	-12.4

4.2.11 Air Leakage

Table 4-14 shows the air leakage loads. The monthly percentage difference between eQUEST and EBLM air leakage load is close to constant throughout the year. The absolute difference is lower in summer months. EBLM users a wind speed adjustment factor. The method of eQUEST used to calculate the volume and air flow rate of the building was not determined within the scope of this thesis. The methods of calculating wind speed effect, volume, and air flow rate of the building may cause the variation.

Table 4-14 Air Leakage comparison results

Air Leakage	eQUEST		EBLM	Difference (%)	Absolute Difference (kWh)
Month	Sensible Load (MBtu)	Sensible Load (MWh)	Sensible Load (MWh)		
January	-22.4	-6.6	-7.5	-15%	1.0
February	-20.2	-5.9	-6.8	-15%	0.9
March	-18.3	-5.3	-6.2	-15%	0.8
April	-12.8	-3.8	-4.3	-14%	0.5
May	-8.3	-2.4	-2.7	-12%	0.3
June	-3.5	-1.0	-1.1	-10%	0.1
July	-1.0	-0.3	-0.3	-11%	0.0
August	-1.7	-0.5	-0.6	-15%	0.1
September	-5.5	-1.6	-1.8	-14%	0.2
October	-11.0	-3.2	-3.7	-14%	0.5
November	-14.2	-4.2	-4.9	-17%	0.7
December	-19.6	-5.8	-6.6	-15%	0.9
Total	-139	-41	-47	-15%	6.0

4.2.13 Ventilation

Table 4-15 shows the ventilation loads only for EBLM. There is no output option from eQUEST to report ventilation loads. The Engineers Manual DOE-2 1982 does not provide information on the calculation of ventilation loads (DOE-2 1982). However, ventilation does add to heating and cooling loads reported by eQUEST.

Table 4-15 Ventilation results (only EBLM)

Ventilation	eQUEST	EBLM	Difference (%)	Absolute Difference (MWh)
Month	Total Energy (MWh)	Total Energy (MWh)		
January	N/A	-21.7	N/A	N/A
February	N/A	-19.6	N/A	N/A
March	N/A	-17.4	N/A	N/A
April	N/A	-11.5	N/A	N/A
May	N/A	-6.3	N/A	N/A
June	N/A	-1.4	N/A	N/A
July	N/A	0.8	N/A	N/A
August	N/A	-0.2	N/A	N/A
September	N/A	-4.1	N/A	N/A
October	N/A	-9.8	N/A	N/A
November	N/A	-14.0	N/A	N/A
December	N/A	-19.1	N/A	N/A
Total	N/A	-124	N/A	N/A

4.2.15 Annual Building Load

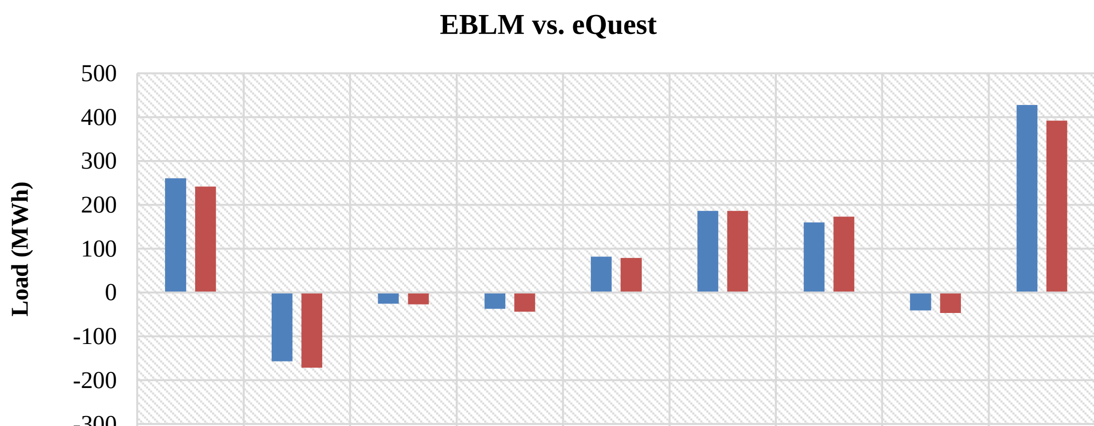
Table 4-16 shows the total annual building loads for each component except the ventilation load. Roof and air leakage have higher percentage differences. Window conduction and plug load have higher absolute differences. The total percentage difference (summing all components) is 8%.

Table 4-16 Annual building load comparison results (without ventilation), and the total building load is the sum of the absolute value of each building component

Annual Building Loads Summary	eQUEST Total Load (MWh)	EBLM Total Load (MWh)	Difference (%)	Absolute Difference (MWh)
Solar Gain - Windows	261	242	7%	19.4
Conduction - Windows	-157	-171	-8%	13.2
Walls	-25.6	-26.8	-4%	1.1
Roof	-36.9	-43.5	-18%	6.5
Occupants	81.6	79.3	3%	2.3
Lighting	186	186	0%	-0.1
Plug Load	160	173	7%	-12.4
Air Leakage	-40.6	-46.6	-15%	6.0
Total	428	392	8%	36.0

4.3 Conclusion

In summary Figure 4-5 provides a convenient way to see the difference between EBLM and eQUEST simulations. Results obtained from eQUEST and EBLM do not differ appreciably. Some individual component results differ but absolute differences are generally very small. Determining the reasons for specific variations can be difficult because of the lack of information on eQUEST calculation methods. Comparing EBLM with other well documented building modeling programs may be useful in future extensions of this work. However through the above comparison, it has been demonstrated that EBLM provides reasonable results, and more importantly EBLM is easier to use and simpler at the early design stage. This result should not be surprising because EBLM only uses established (previously validated) models. The favourable comparison shown in Figure 4-5 provides assurance that these models have been properly implemented.



	Solar Gain - Windows	Con-duction - Windows	Walls	Roof	Occu-pants	Lighting	Plug Load	Air Leakage	Total
eQUEST	261	-157	-25.6	-36.9	81.6	186	160	-40.6	428
EBLM	242	-171	-26.8	-43.5	79.3	186	173	-46.6	392

Figure 4-5 Summary of building component load comparison

5.0 Demonstration of Important Building Factors

EBLM has been compared with eQUEST in the previous chapter. The current chapter presents the results of various simulations to demonstrate the functionality of EBLM and the importance of specific design choices that can be explored using EBLM. The first simulation demonstrates the impact on building energy performance of selecting different specifications of buildings (i.e. conventional versus high-performance design). The second investigation examines the effect of a shading system including locations of slat-type shading, fixed versus operable shading, and various control strategies for operable shading systems. The final simulation is meant to explore how WWR affects overall building performance.

5.1 Energy Performance for Base, High-Performance, and Best-in-Class Building Models

In this section, three building models were created to demonstrate the impact of several different component specifications on building energy performance. Table 5-1 shows the key design parameters that were changed. They are categorized as base building model, high-performance building model, and best-in-class building model. The base building model represents a building constructed in the 1990s. The high-performance building model represents a current energy efficient building. The best-in-class building model represents a building that is well beyond (e.g., more insulation) the current building standard, and attempts to consider a future, low-energy building design. This comparison was carried out with WWR held constant at a value of 40% and with no window shading.

Table 5-1 Specification of base, high performance, and best-in-class building models

Specification	Base Building	High-performance Building	Best-In-Class Building
Wall (R-value)	10	20	25
Roof (R-Value)	15	20	30
WWR (%)	40	40	40
Total Window U-Value (W/m^2 ℃)	2.53	2	1.7
Window SHGC	0.45	0.34	0.34
Solar Transmittance τ_{sol}	0.3	0.18	0.18
Lighting Power Density (W/m^2)	15	9	7.5
Plug Load (W/m^2)	9	8.5	8
Air Leakage (ACH) in service	1	0.7	0.35
Thermal Mass	Brick wall, concrete roof, and medium size (building) with carpet		
Heat Recovery Ventilation (HRV)	None	60%	75%
Shading	None	None	None

5.1.1 Comparison of Building Loads

Table 5-2 shows the comparison of calculated values of building loads by individual building component of three models. The negative sign indicates heating load, and the positive sign means cooling load. Building component loads decrease significantly from the base model to best-in-class model, especially due to improvements in the lighting, building enclosure components, ventilation and air leakage.

Table 5-2 Loads comparison of building components

Annual Building Loads Summary	Base Model	High-performance Model	Best-In-Class Model	Percentage Difference from Base to Upgrade 2 model
	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)	
Solar Gain - Windows	134	101	101	25%
Conduction - Windows	-206	-163	-138	33%
Walls	-53	-26	-21	60%
Roof	-61	-46	-30	51%
Occupants	79	79	79	0%
Lighting	287	172	144	50%
Plug Load	172	163	153	11%
Air Leakage	-575	-402	-201	65%
Ventilation	-133	-53	-33	75%

Table 5-3 is the summary table for the comparison of monthly building loads as calculated for the three building options (see Appendix D for the bar-chart summary of the comparison of monthly building loads). The high-performance model has much smaller loads for each month than the base model. The best-in-class model has even smaller loads except for the months of May and September. This is due to the higher performance enclosure of the best-in-class building that keeps internal heat generation inside the building. Table 5-4 is the annual heating and cooling load comparison of three building models, which shows a significant heating load reduction from the base model to best-in-class model and an improvement on cooling load from base model to high-performance. However, the cooling load slightly increases from high-performance model to best-in-class model due to the very highly insulated enclosure of the best-in-class model.

Table 5-3 Monthly building loads comparison

Monthly Building Loads Summary	Base Model	High-performance Model	Best-In-Class Model
	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)
January	-117	-73	-32
February	-103	-64	-27
March	-81	-48	-16
April	-38	-20	1
May	3	7	19
June	38	30	33
July	59	45	42
August	50	39	38
September	20	18	25
October	-24	-11	7
November	-61	-36	-11
December	-100	-61	-26

Table 5-4 Heating and cooling load comparison of three building models

Heating and Cooling Load	Cooling Load (MWh)	Heating Load (MWh)
Base Model	257	-617
High-performance Model	208	-387
Best-In-Class Model	234	-183

5.1.2 System Load Analysis

Table 5-5 shows mechanical system efficiencies of three building models. The base model has a cooling COP of 2.5, and heating efficiency of 0.68. These numbers are typical for a building constructed in the 1990s. The high-performance model and best-in-class model have better cooling COPs and the heating efficiencies correspond to condensing sealed-combustion devices.

Table 5-5 Mechanical system efficiencies of three building models

	Cooling (COP)	Heating (Efficiency)
Base Model	2.5	0.68
High-performance Model	3.0	0.90
Best-In-Class Model	3.3	0.95

Table 5-6 is a summary of the energy consumption of three models. As expected, the best-in-class model significantly outperforms the other models. The total energy required for heating system of the best-in-class model is only 21% that of the base model, and 45% that of the high-performance model. The required energy for mechanical cooling of the best-in-class model is about 69% that of the base model, and 2 MWh or 3% higher than that of the high-performance model. In terms of total heating and cooling energy, the best-in-class model requires 27% that of the base model, and 53% of that required by the high-performance model.

Table 5-6 Building Cooling and Heating Energy of the three building models

Energy Consumption (Input Energy)	Cooling (MWh)	Heating (MWh)	Total (MWh)
Base Model	103	-907	1010
High-performance Model	69	-430	499
Best-In-Class Model	71	-193	264

As per the results above, the specifications of major building components significantly affect the overall building loads. In addition to building enclosure specifications, the mechanical system design used to meet the loads is important. High efficiency mechanical equipment can make significant reductions in energy use.

5.2 Effect of Different Shading Locations

The high-performance building model was chosen as a reference to demonstrate the influence of different shading locations for better describe the current energy-efficient building. In this comparison, all building components remain constant at values prescribed in Table 5-1except the shading system.

Figure 5-1 is a sketch of indoor, interstitial, and outdoor shading locations. Table 5-7 provides the summary of the glazing and shading specifications that are used here.

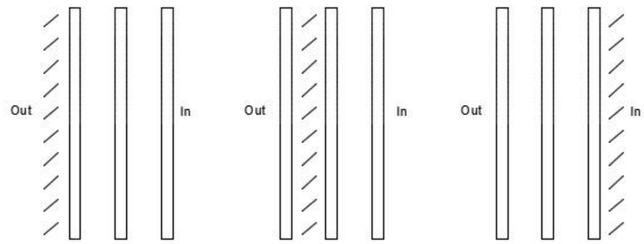


Figure 5-1 Shading locations for triple-glazing system (from left to right: Outdoor, interstitial, and Indoor)

Table 5-7 Summary of shading specification for indoor, interstitial, and outdoor – slat type shading

Specification	**EBLM-High-performance Model-no Shade**	**EBLM-High-performance Model-Indoor**	**EBLM-High-performance Model-interstitial**	**EBLM-High-performance Model-Outdoor**
Shading Location	N/A	Indoor	Interstitial	Outdoor
Number of Glazing Layers	3	3	3	3
Glazing Thickness (mm)	6	6	6	6
Low-e	0.05	0.05	0.05	0.05
Spacing (mm)	13	13	13	13
Gas Fill	Argon	Argon	Argon	Argon
Reflectance	N/A	0.6	0.6	0.6
Open Position	N/A	Opened	Opened	Retracted
IAC_0	1	0.87	0.59	0.24
IAC_{60}	1	0.84	0.48	0.06
IAC_{diff}	1	0.9	0.69	0.36

5.2.1 Fixed Shading

In this comparison, the slat angle of all shading systems is 45 degrees, as shown in Figure 5-1, throughout the year to avoid transmission of direct solar radiation.

Table 5-8 is the summary of calculated building loads for the unshaded case compared to fixed shades at the indoor, interstitial, and outdoor shading locations (Appendix D provides details of the monthly building loads summary for each case). The annual solar gain is reduced by 15% from unshaded to indoor shading, by 31% from indoor to interstitial shading, and by 61% from interstitial to outdoor shading. The annual solar gain is reduced by 77% from an unshaded configuration to a building with fixed outdoor shading. This result demonstrates that it is very effective to reduce solar gain using outdoor shading.

Table 5-8 Building loads for various fixed shading locations at 45 degree slat angle (annual building load is the sum of all components regardless to the signs)

Annual Building Loads Summary (Fixed Shading at 45 Slat Angle)	EBLM-High-performance Model-No Shade	EBLM-High-performance Model-Indoor	Percentage Difference wrt no Shade	EBLM-High-performance Model-interstitial	Percentage Difference wrt indoor shading	EBLM-High-performance Model-Outdoor	Percentage Difference wrt interstitial shading
	Total Load (MWh)	Total Load (MWh)	%	Total Load (MWh)	%	Total Load (MWh)	%
Solar Gain - Windows	101	86	15%	59	31%	23	61%
Conduction - Windows	-163	-163	0%	-163	0%	-163	0%
Walls	-26	-26	0%	-26	0%	-26	0%
Roof	-46	-46	0%	-46	0%	-46	0%
Occupants	79	79	0%	79	0%	79	0%
Lighting	172	172	0%	172	0%	172	0%
Plug Load	163	163	0%	163	0%	163	0%
Air Leakage	-402	-402	0%	-402	0%	-402	0%
Ventilation	-53	-53	0%	-53	0%	-53	0%

In contrast, cooling/heating loads are not so strongly affected by shading because other loads must be considered. Table 5-9 is the summary of heating and cooling loads calculated for the four shading configurations. The cooling load of the fixed outdoor shading system is the lowest because the outdoor shade blocks solar gain most effectively. However, the heating load of the fixed outdoor shading system is the highest because there is less solar gain to offset the heating load in winter months. An interesting phenomenon is that the indoor shading has a limited effect on the total heating and cooling load for the high performance glazing system. However, as the shading system moves from indoor to interstitial or outdoor, a noticeable reduction on the total heating and cooling loads is observed. Wright (2009) offered a similar conclusion; indoor shading attachments offer little potential for controlling the solar gain of low-SHGC glazing systems (high performance glazing systems), and the solar gain of any glazing system can be better controlled by an outdoor shading system.

Table 5-9 Heating and cooling load of various shading locations

Heating and Cooling Load (Fixed Shading at 45 Slat Angle)	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
EBLM-High-performance Model-No Shade	208	-387	595
EBLM-High-performance Model-Indoor	199	-392	591
EBLM-High-performance Model-interstitial	182	-403	585
EBLM-High-performance Model-Outdoor	161	-417	579

5.2.2 Operable Shading

There are advantages (reducing cooling load) and disadvantages (increasing heating load) on building performance in using a fixed outdoor shading system. The disadvantage can be significantly reduced if the outdoor shading system can be automatically opened/closed in response to weather conditions. In this section, the EBLM tool was used to explore various operable shading control strategies. Simulations were performed to optimize function of an operable shading system to reduce both heating and cooling load. Various control strategies, as discussed earlier, are explored to demonstrate how these strategies affect the building performance.

5.2.2.1 Operable Shading Control Strategies

Three control strategies were considered. The blinds were operated based on outdoor temperature, incident solar intensity, and a combination of both outdoor temperature and incident solar intensity. Blinds are operated during all hours. For example, if the outdoor temperature control strategy is chosen, the blind may be closed at night for a specific hour (outdoor temperature is greater than the trigger point at that specific hour) although this action has no influence on solar gain or heat transfer.

5.2.2.1.1 Outdoor Temperature Control Strategy

Table 5-10 shows the results of heating and cooling load calculations for a changing the outdoor temperature limit over a range of values from indoor temperature minus 0℃) to (indoor temperature minus 20 ℃). This exercise was done to explore the impact of choice of outdoor temperature limit on the load calculations. As the outdoor temperature limit decreases, the cooling load decreases, but the heating load increases. Using an outdoor temperature limit of outdoor temperature minus 15 ℃ (7 ℃ outdoor temperature) results in the lowest total load.

Table 5-10 Heating and cooling load by changing outdoor temperature limit for outdoor operable shading

Heating and Cooling Load	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
EBLM-High-performance Model (-0 ℃)	182	-395	577
EBLM-High-performance Model (-5 ℃)	176	-396	571
EBLM-High-performance Model (-10 ℃)	169	-396	565
EBLM-High-performance Model (-15 ℃)	164	-398	561
EBLM-High-performance Model (-20 ℃)	162	-402	564

Table 5-11 shows the heating and cooling load that results from setting the outdoor temperature limit to 7 ℃ for an indoor temperature difference of minus 15 ℃. (Appendix D contains the summary of monthly building loads for the outdoor temperature control strategy). The use of outdoor operable shading and a 7 ℃ trigger point results in the lowest combined total heating and cooling load. It can be seen by comparing results in Table 5-9 and Table 5-11 that the cooling load with outdoor operable shading and a 7 ℃ trigger point is higher than the fixed outdoor shading. However, the total heating and cooling load is smaller than the total heating and cooling load of the fixed outdoor shading because the operable shading system allows solar gain entering the building to offset the heat load.

Table 5-11 Heating and cooling load by setting the outdoor temperature limit to 7 ℃ (outdoor temperature minus 15 ℃)

Heating and Cooling Load - Operable Temperature (Low SHGC)	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
EBLM-High-performance Model-No Shade	208	-387	595
EBLM-High-performance Model-Indoor	179	-392	570
EBLM-High-performance Model-interstitial	173	-394	567
EBLM-High-performance Model-Outdoor	164	-398	561

5.2.2.1.2 Outdoor Temperature Control Strategy with Changing Solar Heat Gain Coefficient

In order to reduce the heating load, the outdoor temperature control strategy can be modified by increasing the glazing system SHGC to collect more solar gain. Table 5-12 summarizes a list of SHGC values that were used for different shading locations. Since solar gain can be effectively controlled with an automated outdoor shade, there may be a benefit to increase the SHGC of the glazing system, allowing more solar heat gain when heating is required.

Table 5-12 Different glazing system used in conjunction with different shading locations

Used with no shade or indoor shading	**SHGCcg (θ=0)**	0.34
Used with interstitial shading	**SHGCcg (θ=0)**	0.45
Used with outdoor shading	**SHGCcg (θ=0)**	0.60

Table 5-13 is the summary of heating and cooling loads calculated for the high SHGC glazing with the outdoor temperature shading control strategy as described in section 5.2.2.1.1 (Appendix D provides the summary of monthly building loads for the high SHGC outdoor temperature control strategy). For the high SHGC glazing, both heating and cooling loads for the outdoor operable shading system are lower than the loads with no shade. The heating load of the high SHGC glazing (outdoor operable shading) is smaller than that with the low SHGC glazing (Table 5-11). However, the cooling load is significantly higher than that of the low SHGC glazing shown in Table 5-11. In terms of the total combined heating and cooling load, the low SHGC glazing outdoor temperature control strategy is better than the high SHGC outdoor temperature control strategy.

Table 5-13 Heating and cooling load for the high SHGC glazing

Heating and Cooling Load - Operable Temperature (High SHGC)	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
EBLM-High-performance Model-No Shade	208	-387	595
EBLM-High-performance Model-Indoor	179	-392	570
EBLM-High-performance Model-interstitial	185	-385	570
EBLM-High-performance Model-Outdoor	184	-381	565

5.2.2.1.3 Solar Incident Intensity Control Strategy

The solar incident intensity control strategy operates the shades based on the incoming solar intensity. For this set of simulations, a range of solar incident intensity limits from 250 to 400 W/m^2 was chosen. The calculated heating and cooling load results for those simulations are summarized in Table 5-14.

Table 5-14 Heating and cooling load by changing solar intensity limit for outdoor operable shading

	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
EBLM-High-performance Model-No Shade	208	-387	595
EBLM-High-performance Model (450 W/m^2)	171	-414	585
EBLM-High-performance Model (400 W/m^2)	168	-415	583
EBLM-High-performance Model (350 W/m^2)	166	-416	582
EBLM-High-performance Model (300 W/m^2)	165	-417	581
EBLM-High-performance Model (250 W/m^2)	163	-418	581

Using a solar incident intensity limit of 250 W/m^2 obtained the lowest associated heating and cooling loads. Similar to the outdoor temperature control strategy, the outdoor operable shading system has the lowest cooling load, and the highest heating load as shown in Table 5-15 (Appendix D contains the summary of monthly building loads for the modified outdoor temperature control strategy). The outdoor operable shading system with the outdoor temperature control strategy has better performance with respect to heating and cooling load versus a similar shading system with solar incident intensity control strategy. This result occurs because the blinds are closed during numerous cold hours during which the solar gain would be useful to offset the heating load.

Table 5-15 Heating and cooling load for solar intensity based control strategy

Heating and Cooling Load - Operable Solar Intensity Based (250 W/m^2)	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
EBLM-High-performance Model-No Shade	208	-387	595
EBLM-High-performance Model-Indoor	178	-411	588
EBLM-High-performance Model-interstitial	173	-413	586
EBLM-High-performance Model-Outdoor	163	-418	581

5.2.2.1.4 Combination of Outdoor Temperature and Solar Intensity Control Strategy

A combination of outdoor temperature and solar incident intensity control strategy can be used to obtain advantages from both strategies. The outdoor temperature and solar incident intensity limits were set at 7 ℃ and 250 W/m^2 based on the results of the previous simulations. The shade is not used if the outdoor temperature or solar incident intensity is within the specified limit. More specifically the shade is used if both outdoor temperature and solar incident intensity are above their respective limits. The cooling load is higher than those of outdoor temperature and solar incident intensity control strategies, but the heating load is lower than that of solar incident intensity control strategy as shown in Table 5-16 (Appendix D contains the summary of monthly building loads for the modified outdoor temperature control strategy).

Table 5-16 Heating and cooling load for the combination of outdoor temperature and solar incident intensity control strategy

Heating and Cooling Load - Operable Temperature and Solar Combined Control Strategy	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
EBLM-High-performance Model-No Shade	208	-387	595
EBLM-High-performance Model-Indoor	180	-391	572
EBLM-High-performance Model-interstitial	175	-394	569
EBLM-High-performance Model-Outdoor	165	-398	563

5.2.2.1.5 Summary

Table 5-17 provides a summary of the predicted heating and cooling loads for all shading systems. Results show that fixed and operable indoor shading systems do not result in a significant load reduction. In terms of heating load, the high SHGC glazing with outdoor temperature control strategy is the best option. However, this option also results in the highest cooling load among all strategies with shading. In terms of total heating and cooling load, the low SHGC glazing system with outdoor temperature control strategy seems to provide the best balance between heating and cooling load (the total heating and cooling load is reduced by 5.7%).

Other operable shading control strategies are available for users to explore. Different control strategies may lead to different results of heating and cooling loads. Section 5.2.2.1.2 concludes that the low SHGC glazing system with outdoor temperature control strategy is better than that of the high SHGC glazing system with outdoor temperature control strategy. However, if a different control strategy is chosen, the conclusion may be different. For example, a control strategy of shaded low and high SHGC glazing systems as a function of internal load will lead to the opposite conclusion. In this case, the shade is closed when cooling is required so the required cooling loads for the low SHGC and high SHGC glazing systems must be identical because the cooling load in this case is a function of only internal load (no solar effect). Also, the shade is not used when heating is required. Therefore, the high SHGC glazing system has an advantage of collecting more solar gain to offset the heating load versus the low SHGC glazing system. It can be concluded that the high SHGC glazing system with outdoor shading operated as a function of cooling load is better than that of the low SHGC glazing system.

Table 5-17 Summary of heating and cooling load for four control strategies

Heating and Cooling Load	Operable: Outdoor Temperature Control Strategy (Low SHGC)			Operable: Outdoor Temperature Control Strategy (High SHGC)			Operable: Solar Incident Intensity Control Strategy			Operable: Combination of Outdoor Temperature and Solar Incident Intensity Control Strategy		
	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
EBLM-High-performance Model-No Shade	208	-387	595	208	-387	595	208	-387	595	208	-387	595
EBLM-High-performance Model-Indoor	179	-392	570	179	-392	570	178	-411	588	180	-391	572
EBLM-High-performance Model-Interstitial	173	-394	567	185	-385	570	173	-413	586	175	-394	569
EBLM-High-performance Model-Outdoor	164	-398	561	184	-381	565	163	-418	581	165	-398	563

5.3 Effect of Window-to-Wall Ratio

In order to use the benefit of operable shading system, simulations were performed to explore an optimized WWR. The high-performance building model was chosen as a baseline model to illustrate the effect of the WWR on building performance. WWR of 30%, 40%, 50%, and 60% were used for simulations. Only WWR is changed throughout the simulation process, and other building components remain constant. Table 5-18 is the summary of results (Appendix D provides the summary of monthly building loads for various WWRs). Solar gain and conduction through windows double as WWR increases from 30% to 60%. As the window area increases, the wall area decreases and hence so does the heat transfer through walls.

Table 5-18 Summary of annual building loads for 30%, 40%, 50%, and 60% WWR, and the total building load is the sum of the absolute value of each building component

Annual Building Loads Summary	WWR 30 %	WWR 40 %	WWR 50 %	WWR 60 %
	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)
Solar Gain - Windows	76	101	127	152
Conduction - Windows	-122	-163	-203	-244
Walls	-31	-26	-22	-18
Roof	-46	-46	-46	-46
Occupants	79	79	79	79
Lighting	172	172	172	172
Plug Load	163	163	163	163
Air Leakage	-402	-402	-402	-402
Ventilation	-53	-53	-53	-53

To assess the impact on energy consumption, the heating and cooling loads are summarized in Table 5-19. The WWR of 30% has the lowest heating and cooling loads (reduction about 5.8 % from WWR of 40% to 30%), and heating and cooling loads increase as WWR increases. Reducing the WWR from 40% to 30% has a similar effect as deploying operable shades, intelligently operated, on the exterior of a building with 40% WWR.

Table 5-19 Summary of heating and cooling for different WWRs

Heating and Cooling Load	Cooling Load (MWh)	Heating Load (MWh)	Total (MWh)
30 %	196	-364	560
40 % (baseline)	208	-387	595
50 %	221	-410	631
60 %	233	-434	667

As shading essentially impacts only the solar gain through windows, more investigations are recommended to determine the influence of exterior shades on a building with 60% WWR.

6.0 Conclusions and Recommendations

An understanding of the major building design parameters is an important part of designing a low energy building, especially at the early stage of building design. Modeling software has been developed to assist designers estimate building loads, mechanical system loads, and energy consumption. It is however difficult to predict building loads in the early design stage because most design features have not yet been specified. Most programs require users to supply detailed building specifications, and these specifications are typically unavailable at the beginning of the design stage.

A new modeling tool, an Excel-Based Load Model (EBLM), was created to help designers during the early design stage. The EBLM is intended to be a simple and easy-to-use, yet relatively accurate, modeling tool that integrates building parameters that are known to be critical to heating and cooling loads– for a specific class of building – the mid-sized office building.

The EBLM uses Excel as the calculation engine. This allows designers to modify the program because the code is effectively open source. EBLM uses the conduction time series (CTS) and radiant time series (RTS) methods to account for dynamic solar variations, and thermal storage effects. EBLM also addresses building parameters that are not available in other programs at the early design stage. For example, operable shading systems including the type of shade, location, and control strategy can be modified. EBLM can output hourly, monthly, and annual building loads for individual building components as well as the total heating and cooling load.

Simulations were performed to demonstrate the effects of operable shading systems and WWR on building loads for a generic high performance building design. The following major conclusions were developed.

- Specification of high performance building enclosure design characteristics, such as U-value, low SHGC, etc. can significantly reduce heating and cooling load. Energy-efficient mechanical systems can further reduce energy use.
- Implementing an outdoor shading system is an effective way to reduce solar gain through windows, up to 77% of solar gain was eliminated by switching from no shading to outdoor shading (using a fixed 45^o slat angle). Indoor shading is less effective.
- An outdoor shading system makes a significant reduction on the cooling load, but also increases heating load.
- An operable outdoor shading system also offers the potential to reduce heating load. The lowest energy control strategy investigated was one that closes the blind when the outdoor temperature exceeds a set point. The outdoor temperature control strategy has the best performance of the three control strategies examined.
- Using an outdoor temperature shading control strategy, low SHGC glazing with the outdoor operable shading system has better building performance than high SHGC glazing with the operable shading system in the climate of Toronto.
- Ideally an operable outdoor shading system would be controlled simply on the need for heating or cooling, although this control could be difficult to achieve.
- As others have found, reducing WWR results in significant heating and cooling load reduction.

- A reduction of WWR from 40% to 30% has a similar effect as deploying an outdoor operable shading system.

6.1 Recommendations for Building Design

Specifications of high performance building make a significant load reduction, and are strongly recommended for building designs. WWR and SHGC are dominant factors for solar heat gain, and using low WWR and SHGC is recommended to reduce building loads.

Installing an outdoor shading system is an effective way to reduce building cooling loads, especially an operable and automated outdoor shading system. Using the temperature control strategy and using a low outdoor temperature limit is recommended.

6.2 Recommendations for Future Work

Future studies are recommended to continue the development of EBLM. There are a number of areas for improvement to this model. A core/perimeter zone feature should be added to more realistically model office buildings. Heat loss through slabs-on-grade could be implemented. Other strategies for controlling outdoor shading should be investigated. A basic equipment load calculation would be useful as well so that users can size mechanical equipment.

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Appendix

- Appendix A – EBLM Development

- Appendix B – eQUEST Model

- Appendix C – Simulation Results

Appendix A – EBLM Development

	C	D	E	F	G	H	I	J	K	L	M
1	Hour	Outdoor Dry Bulb Temperature (F)	Outdoor Dry bulb Temperature (0C)	Outdoor Wet Bulb Temperature (0F)	Outdoor web bulb Temperature (0C)	Indoor Dry Bulb Temperature (0C)	Solar Flux on Horizontal Surface (Btu/hr-ft2)	Solar Flux on Horizontal Surface (W/m2)	Wind speed (knots)	Wind Speed (MPH)	Wind Speed (km/h)
2	1	11	-11.7	9.0	-12.8	22	0	0	9	10.4	16.7
3	2	6	-14.4	5.0	-15.0	22	0	0	16	18.4	29.6
4	3	3	-16.1	2.0	-16.7	22	0	0	17	19.6	31.5
5	4	0	-17.8	-1.0	-18.3	22	0	0	20	23.0	37.0
6	5	-1	-18.3	-2.0	-18.9	22	0	0	17	19.6	31.5
7	6	-3	-19.4	-3.0	-19.4	22	0	0	11	12.7	20.4
8	7	-1	-18.3	-2.0	-18.9	22	0	0	10	11.5	18.5
9	8	0	-17.8	-1.0	-18.3	22	1	3	16	18.4	29.6
10	9	-1	-18.3	-2.0	-18.9	22	13	41	13	15.0	24.1
11	10	-1	-18.3	-2.0	-18.9	22	54	170	16	18.4	29.6
12	11	0	-17.8	-1.0	-18.3	22	88	278	19	21.9	35.2
13	12	1	-17.2	0.0	-17.8	22	109	344	21	24.2	38.9
14	13	-1	-18.3	-2.0	-18.9	22	95	300	26	30.0	48.1
15	14	8	-13.3	7.0	-13.9	22	87	274	21	24.2	38.9
16	15	10	-12.2	9.0	-12.8	22	50	158	15	17.3	27.8
17	16	14	-10.0	13.0	-10.6	22	14	44	14	16.1	25.9
18	17	12	-11.1	11.0	-11.7	22	4	13	17	19.6	31.5
19	18	10	-12.2	9.0	-12.8	22	0	0	17	19.6	31.5
20	19	7	-13.9	6.0	-14.4	22	0	0	10	11.5	18.5
21	20	5	-15.0	4.0	-15.6	22	0	0	8	9.2	14.8
22	21	5	-15.0	4.0	-15.6	22	0	0	9	10.4	16.7
23	22	5	-15.0	4.0	-15.6	22	0	0	10	11.5	18.5
24	23	4	-15.6	3.0	-16.1	22	0	0	10	11.5	18.5
25	24	3	-16.1	2.0	-16.7	22	0	0	10	11.5	18.5

Weather input interface of EBLM

	A	B	C
1	Location	Toronto	
2	Latitude	43.7	N
3	Longitude	-79.4	E
4	Eastern	-75	E
5	Sm	23.45	degree
6	Year	2012	
7	Solar Radiation GSC	1367	W/m2

Location of the input model

	A	B	C
9	Dimensions		
10	Length	50	m
11	Width	25	m
12	Height	4	m
13	Number of Floor	3	
14	Single Floor Area	1250	m2
15	Roof Area	1250	m2
16	Volume	15000	m3
17	Door Height	2.74	m
18	Door Width	5.49	m
19	Percentage of Window Frame	10%	
20			
21	WWR	0.4	
22	Total Wall Area for First Floor	342	
23	Total Wall Area for other Floors	360	m2
24	Total Wall Area	1062	m2
25	Total Wall Area for North or South Side for first Floor	111	m2
26	Total Wall Area for East or West Side for first Floor	60	m2
27	Total Window View Area for North or South Side for first Floor	67	m2
28	Total Window View Area for East or West Side for first Floor	36	m2
29	Total Wall Area for North or South Side for other Floors	120	m2
30	Total Wall Area for East or West Side for other Floors	60	m2
31	Total Window View Area for North or South Side for other floors	72	m2
32	Total Window View Area for East or West Side for other floors	36	m2
33	Total Window View Area for first Floor	205	m2
34	Total Window view Area for the other floors	216	m2
35	Total Window Area for the first floor	228	m2
36	Total Window Area for the other floors	240	m2
37	Total Window View area	637	m2
38	Total Window area	708	m2
39	Total Wall Area for North or South	351	m2
40	Total Wall Area for East or South	180	m2
41	Total Window View Area for North or South	211	m2
42	Total Window View Area for East or West	108	m2

Dimensions of the input model

	A	B
44	**Sol-air Property**	
45	**Colour of the Wall**	Dark Colour
46	**Colour of the Roof**	Light Colour
47	**a/ho for Wall**	0.052
48	**a/ho for Roof**	0.026
49	**Orrientation of Wall**	Vertical
50	**Orrientation of Roof**	Horizontal
51	**eR/ho of Wall Vertical (K)**	0
52	**eR/ho of Roof (K)**	4
53		
54	**Structure**	
55	**Type of Walls**	Brick Wall
56	**Type of Roof**	Concrete Roof (High R)
57	**Structure of Building (Nonsolar)**	Medium with Carpet
58	**Structure of building (Soalr)**	Medium with Carpet
59	**Wall and Roof Conductive Fraction**	0.4
60	**Wall and RoofRadiative Fraction**	0.6

Sol-air property and structure of the input model

	A	B	C
59	**Walls and Roof**		
60		R-Value	RSI
61	**Wall**	20	3.52
62	**Roof**	20	3.52
63	**East Wall Surface Azimuth**	-90	degree
64	**South Wall Surface Azimuth**	0	degree
65	**West Wall Surface Azimuth**	90	degree
66	**North Wall Surface Azimuth**	-180	degree
67	**Tilted Angle**	90	degree
68	**Ground Reflective factor p**	0.2	

Specification of walls and roof of the input model

	A	B	C
73	**Glazing Specifications**		
74	**Glazing ID**	33	
75	**Number of glazing units**	3	
76	**Glazing Thickness (mm)**	6	
77	**Low-e**	0.05	
78	**Spacing (mm)**	13	
79	**Gap**	Argon	
80	**T (θ=0)**	0.18	
81	**SHGC (θ=0) with no shade and interior shade**	0.34	
82	**SHGC (θ=0) with interstitial shade**	0.45	
83	**SHGC(θ=0) with Outdoor shade**	0.60	
84	**USI of Window**	2	W/m2C
85	**R-Value of Window**	2.84	m2C/W
86	**USI of Door**	2.00	W/m2C
87	**Rsi of Door**	2.84	m2C/W

Glazing specification of the input model

	A	B
92	**Ventilation & Air Leakage Info**	
93	**Ventilation Schedule**	7 AM to 8 PM
94	**Ventilation Rate at night Schedule (ACH)**	0.05
95	**Ventilation Rate at night Schedule (L/s)**	208
96	**Zone Effectiveness**	1
97	**Heat Recovery Ventilation (HRV)**	0.60
98	**Air Density (kg/m3)**	1.20
99	**Specific Heat of air (J/(kg*K)**	1000
100	**Standard Atmosphere Pressure (Pa)**	101325
101	**Air leakage (ACH)**	0.7
102	**Air Leakage (m3/s)**	2.92
103	**Wind Speed Adjustment**	90%
104	**Occupancy Category**	Office Space
105	**People Outdoor Air Rate (cfm/person)**	5
106	**Area Outdoor Air Rate (cfm/ft2)**	0.06
107	**People Outdoor Air Rate (L/s/person)**	2.36
108	**Area Outdoor Air Rate (L/s/m2)**	0.305

Ventilation and air leakage specification of the input model

	A	B
1	**Occupancy Info**	
2	Radiative Fraction	0.6
3	Convective Fraction	0.4
4	Number of Occupants	135
5	Sensible Portion (W)	70
6	Latent Portion (W)	45
7	Heat Generated per Occupant(W)	115
8	Occupancy Schedule	7 AM to 8 PM
9		
10	**Plug Load Info**	
11	Radiative Fraction	0.6
12	Convective Fraction	0.4
13	Plug Loads (W/m2)	8.5
14	Plug Loads Schedule	7 AM to 8 PM
15		
16	**Luminaire Type: Recessed fluorescent luminaire without lens, average**	
17	Radiative Fraction	0.42
18	Convective Fraction	0.58
19	Lighting Power Density (W/m2)	9
20	Lighting Schedule	7 AM to 8 PM

Internal heat generation of the input model

H	I	J	K	L
Roof Conduction Time Series (CTS)				
Roof Number	1	2	3	4
Roof Type	Wood Deck	Metal Deck Roof	Concrete Roof (low R)	Concrete Roof (High R)
Total R (m2K/W)	2.5	3.1	3.3	3.5
Hour	**Conduction Time Factors (%)**			
1	0%	8%	1%	2%
2	7%	53%	2%	2%
3	18%	30%	8%	3%
4	18%	7%	11%	4%
5	15%	2%	11%	5%
6	11%	0%	10%	6%
7	8%	0%	9%	6%
8	6%	0%	7%	6%
9	5%	0%	6%	6%
10	3%	0%	5%	6%
11	3%	0%	5%	6%
12	2%	0%	4%	5%
13	1%	0%	3%	5%
14	1%	0%	3%	5%
15	1%	0%	3%	4%
16	1%	0%	2%	4%
17	0%	0%	2%	4%
18	0%	0%	2%	4%
19	0%	0%	1%	3%
20	0%	0%	1%	3%
21	0%	0%	1%	3%
22	0%	0%	1%	3%
23	0%	0%	1%	3%
24	0%	0%	1%	2%

Roof conduction time factors

N	O	P	Q	R	S	T
Nonsolar RTS Value for Light to Heavy Construction						
Structures	Light		Medium		Heavy	
	With Carpet	Without Carpet	With Carpet	Without Carpet	With Carpet	Without Carpet
WWR	50%	50%	50%	50%	50%	50%
Hour	Radiant Time Factors (%)					
1	50%	43%	49%	33%	38%	25%
2	18%	19%	17%	16%	9%	9%
3	10%	11%	9%	10%	6%	6%
4	6%	7%	5%	7%	4%	5%
5	4%	5%	3%	5%	4%	5%
6	3%	3%	2%	4%	3%	4%
7	2%	3%	2%	3%	3%	4%
8	1%	2%	1%	3%	3%	4%
9	1%	1%	1%	2%	3%	3%
10	1%	1%	1%	2%	3%	3%
11	1%	1%	1%	2%	2%	3%
12	1%	1%	1%	2%	2%	3%
13	1%	1%	1%	1%	2%	3%
14	1%	1%	1%	1%	2%	3%
15	0%	1%	1%	1%	2%	2%
16	0%	0%	1%	1%	2%	2%
17	0%	0%	1%	1%	2%	2%
18	0%	0%	1%	1%	2%	2%
19	0%	0%	1%	1%	2%	2%
20	0%	0%	1%	1%	2%	2%
21	0%	0%	0%	1%	1%	2%
22	0%	0%	0%	1%	1%	2%
23	0%	0%	0%	1%	1%	2%
24	0%	0%	0%	0%	1%	2%

Nonsolar RTS factors for light to heavy construction

V	W	X	Y	Z	AA	AB
Solar RTS Value for Light to Heavy Construction						
Structures	Light		Medium		Heavy	
	With Carpet	Without Carpet	With Carpet	Without Carpet	With Carpet	Without Carpet
WWR	50%	50%	50%	50%	50%	50%
Hour	Radiant Time Factors (%)					
1	55%	45%	54%	29%	49%	27%
2	17%	20%	16%	15%	12%	13%
3	9%	11%	8%	10%	6%	7%
4	5%	7%	4%	7%	4%	5%
5	3%	5%	3%	6%	3%	4%
6	2%	3%	2%	5%	2%	4%
7	2%	2%	1%	4%	2%	3%
8	1%	2%	1%	3%	2%	3%
9	1%	1%	1%	3%	2%	3%
10	1%	1%	1%	3%	2%	3%
11	1%	1%	1%	2%	2%	3%
12	1%	1%	1%	2%	2%	3%
13	1%	1%	1%	2%	1%	2%
14	1%	0%	1%	2%	1%	2%
15	0%	0%	1%	1%	1%	2%
16	0%	0%	1%	1%	1%	2%
17	0%	0%	1%	1%	1%	2%
18	0%	0%	1%	1%	1%	2%
19	0%	0%	1%	1%	1%	2%
20	0%	0%	0%	1%	1%	2%
21	0%	0%	0%	1%	1%	2%
22	0%	0%	0%	0%	1%	2%
23	0%	0%	0%	0%	1%	1%
24	0%	0%	0%	0%	1%	1%

Solar RTS factors for light to heavy construction

	A	B	C	D	E	F	G	H	I	J	K
1	**Month**	**Day**	**Hour**	**Normal Lighting Schedule**	**Busy Lighting Schedule**	**Normal Plug Loads Schedule**	**Busy Plug Loads Schedule**	**Normal Occupancy Schedule**	**Busy Occupancy Schedule**	**Normal Ventilation Schedule**	**Busy Ventilation Schedule**
2	1	1	1	0%	0%	0%	0%	0	0	Night	Night
3	1	1	2	0%	0%	0%	0%	0	0	Night	Night
4	1	1	3	0%	0%	0%	0%	0	0	Night	Night
5	1	1	4	0%	0%	0%	0%	0	0	Night	Night
6	1	1	5	0%	0%	0%	0%	0	0	Night	Night
7	1	1	6	0%	0%	0%	100%	0	0	Night	Night
8	1	1	7	100%	100%	100%	100%	135	0	Day	Night
9	1	1	8	100%	100%	100%	100%	135	135	Day	Day
10	1	1	9	100%	100%	100%	100%	135	135	Day	Day
11	1	1	10	100%	100%	100%	100%	135	135	Day	Day
12	1	1	11	100%	100%	100%	100%	135	135	Day	Day
13	1	1	12	100%	100%	100%	100%	135	135	Day	Day
14	1	1	13	100%	100%	100%	100%	135	135	Day	Day
15	1	1	14	100%	100%	100%	100%	135	135	Day	Day
16	1	1	15	100%	100%	100%	100%	135	135	Day	Day
17	1	1	16	100%	100%	100%	100%	135	135	Day	Day
18	1	1	17	100%	100%	100%	100%	135	135	Day	Day
19	1	1	18	100%	100%	100%	100%	135	135	Day	Day
20	1	1	19	100%	100%	100%	100%	135	135	Day	Day
21	1	1	20	100%	100%	100%	100%	135	135	Day	Day
22	1	1	21	0%	100%	0%	100%	0	135	Night	Day
23	1	1	22	0%	100%	0%	100%	0	0	Night	Day
24	1	1	23	0%	100%	0%	0%	0	0	Night	Day

Operating schedules for 24 hours

	A	B	C	D	E	F	G	H	I	J
1			**Cooling Load Component: Lighting**							
2					**Heat Gain (W)**					
3						**Convective**	**Radiant**			
4	**Month**	**Day**	**Hour**	**Usage Profile (%)**	**Total**	**58%**	**42%**	**Nonsolar RTS**	**Radiant Cooling Load (W)**	**Total Sensible Cooling Load for Lighting (W)**
29	1	1	1	0%	0	0	0	49%	2268	2268
30	1	1	2	0%	0	0	0	17%	2126	2126
31	1	1	3	0%	0	0	0	9%	1843	1843
32	1	1	4	0%	0	0	0	5%	1701	1701
33	1	1	5	0%	0	0	0	3%	1559	1559
34	1	1	6	0%	0	0	0	2%	1418	1418
35	1	1	7	100%	33750	19575	14175	2%	8222	27797
36	1	1	8	100%	33750	19575	14175	1%	10490	30065
37	1	1	9	100%	33750	19575	14175	1%	11624	31199
38	1	1	10	100%	33750	19575	14175	1%	12191	31766
39	1	1	11	100%	33750	19575	14175	1%	12474	32049
40	1	1	12	100%	33750	19575	14175	1%	12616	32191
41	1	1	13	100%	33750	19575	14175	1%	12758	32333
42	1	1	14	100%	33750	19575	14175	1%	12758	32333
43	1	1	15	100%	33750	19575	14175	1%	12758	32333
44	1	1	16	100%	33750	19575	14175	1%	12758	32333
45	1	1	17	100%	33750	19575	14175	1%	12899	32474
46	1	1	18	100%	33750	19575	14175	1%	13041	32616
47	1	1	19	100%	33750	19575	14175	1%	13183	32758
48	1	1	20	100%	33750	19575	14175	1%	13325	32900
49	1	1	21	0%	0	0	0	0%	6521	6521
50	1	1	22	0%	0	0	0	0%	4253	4253
51	1	1	23	0%	0	0	0	0%	3119	3119
52	1	1	24	0%	0	0	0	0%	2552	2552

24-hour load calculation for lighting

	A	B	C	D	E	F	G	H	I	J
1	**Cooling Load Component:Plug Load**									
2					**Heat Gain (W)**					
3						Convective	Radiant			
4	**Month**	**Day**	**Hour**	**Usage Profile (%)**	**Total**	**40%**	**60%**	**Nonsolar RTS**	**Radiant Cooling Load (W)**	**Total Sensible Cooling Load Plug Load (W)**
29	1	1	1	0%	0	0	0	49%	3060	3060
30	1	1	2	0%	0	0	0	17%	2869	2869
31	1	1	3	0%	0	0	0	9%	2486	2486
32	1	1	4	0%	0	0	0	5%	2295	2295
33	1	1	5	0%	0	0	0	3%	2104	2104
34	1	1	6	0%	0	0	0	2%	1913	1913
35	1	1	7	100%	31875	12750	19125	2%	11093	23843
36	1	1	8	100%	31875	12750	19125	1%	14153	26903
37	1	1	9	100%	31875	12750	19125	1%	15683	28433
38	1	1	10	100%	31875	12750	19125	1%	16448	29198
39	1	1	11	100%	31875	12750	19125	1%	16830	29580
40	1	1	12	100%	31875	12750	19125	1%	17021	29771
41	1	1	13	100%	31875	12750	19125	1%	17213	29963
42	1	1	14	100%	31875	12750	19125	1%	17213	29963
43	1	1	15	100%	31875	12750	19125	1%	17213	29963
44	1	1	16	100%	31875	12750	19125	1%	17213	29963
45	1	1	17	100%	31875	12750	19125	1%	17404	30154
46	1	1	18	100%	31875	12750	19125	1%	17595	30345
47	1	1	19	100%	31875	12750	19125	1%	17786	30536
48	1	1	20	100%	31875	12750	19125	1%	17978	30728
49	1	1	21	0%	0	0	0	0%	8798	8798
50	1	1	22	0%	0	0	0	0%	5738	5738
51	1	1	23	0%	0	0	0	0%	4208	4208
52	1	1	24	0%	0	0	0	0%	3443	3443

24-hour load calculation for plug load

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1			**Cooling Load Component: Occupant**											
2					**Heat Gain (W)**									
3								**Convective**	**Radiant**					
4	**Month**	**Day**	**Hour**	**Number of Occupant**	**Total**	**Sensible Heat**	**Latent Heat**	**40%**	**60%**	**Nonsolar RTS**	**Radiant Cooling Load (W)**	**Total Sensible Cooling (W)**	**Total Latent Cooling (W)**	**Total Cooling Load for Occupant (W)**
29	1	1	1	0	0	0	0	0	0	49%	907	907	0	907
30	1	1	2	0	0	0	0	0	0	17%	851	851	0	851
31	1	1	3	0	0	0	0	0	0	9%	737	737	0	737
32	1	1	4	0	0	0	0	0	0	5%	680	680	0	680
33	1	1	5	0	0	0	0	0	0	3%	624	624	0	624
34	1	1	6	0	0	0	0	0	0	2%	567	567	0	567
35	1	1	7	135	15525	9450	6075	3780	5670	2%	3289	7069	6075	13144
36	1	1	8	135	15525	9450	6075	3780	5670	1%	4196	7976	6075	14051
37	1	1	9	135	15525	9450	6075	3780	5670	1%	4649	8429	6075	14504
38	1	1	10	135	15525	9450	6075	3780	5670	1%	4876	8656	6075	14731
39	1	1	11	135	15525	9450	6075	3780	5670	1%	4990	8770	6075	14845
40	1	1	12	135	15525	9450	6075	3780	5670	1%	5046	8826	6075	14901
41	1	1	13	135	15525	9450	6075	3780	5670	1%	5103	8883	6075	14958
42	1	1	14	135	15525	9450	6075	3780	5670	1%	5103	8883	6075	14958
43	1	1	15	135	15525	9450	6075	3780	5670	1%	5103	8883	6075	14958
44	1	1	16	135	15525	9450	6075	3780	5670	1%	5103	8883	6075	14958
45	1	1	17	135	15525	9450	6075	3780	5670	1%	5160	8940	6075	15015
46	1	1	18	135	15525	9450	6075	3780	5670	1%	5216	8996	6075	15071
47	1	1	19	135	15525	9450	6075	3780	5670	1%	5273	9053	6075	15128
48	1	1	20	135	15525	9450	6075	3780	5670	1%	5330	9110	6075	15185
49	1	1	21	0	0	0	0	0	0	0%	2608	2608	0	2608
50	1	1	22	0	0	0	0	0	0	0%	1701	1701	0	1701
51	1	1	23	0	0	0	0	0	0	0%	1247	1247	0	1247
52	1	1	24	0	0	0	0	0	0	0%	1021	1021	0	1021

24-hour load calculation for occupancy

	A	B	C	D	E	F
1	**Month**	**Day**	**Hour**	**Outdoor Dry bulb Temperature (0C)**	**Indoor Dry Bulb Temperature (0C)**	**Ventilation (W)**
2	1	1	1	-11.7	22	-3408
3	1	1	2	-14.4	22	-3690
4	1	1	3	-16.1	22	-3858
5	1	1	4	-17.8	22	-4027
6	1	1	5	-18.3	22	-4083
7	1	1	6	-19.4	22	-4196
8	1	1	7	-18.3	22	-28536
9	1	1	8	-17.8	22	-28143
10	1	1	9	-18.3	22	-28536
11	1	1	10	-18.3	22	-28536
12	1	1	11	-17.8	22	-28143
13	1	1	12	-17.2	22	-27749
14	1	1	13	-18.3	22	-28536
15	1	1	14	-13.3	22	-24998
16	1	1	15	-12.2	22	-24212
17	1	1	16	-10.0	22	-22640
18	1	1	17	-11.1	22	-23426
19	1	1	18	-12.2	22	-24212
20	1	1	19	-13.9	22	-25391
21	1	1	20	-15.0	22	-26177
22	1	1	21	-15.0	22	-3746
23	1	1	22	-15.0	22	-3746
24	1	1	23	-15.6	22	-3802
25	1	1	24	-16.1	22	-3858

24-hour load calculation for ventilation

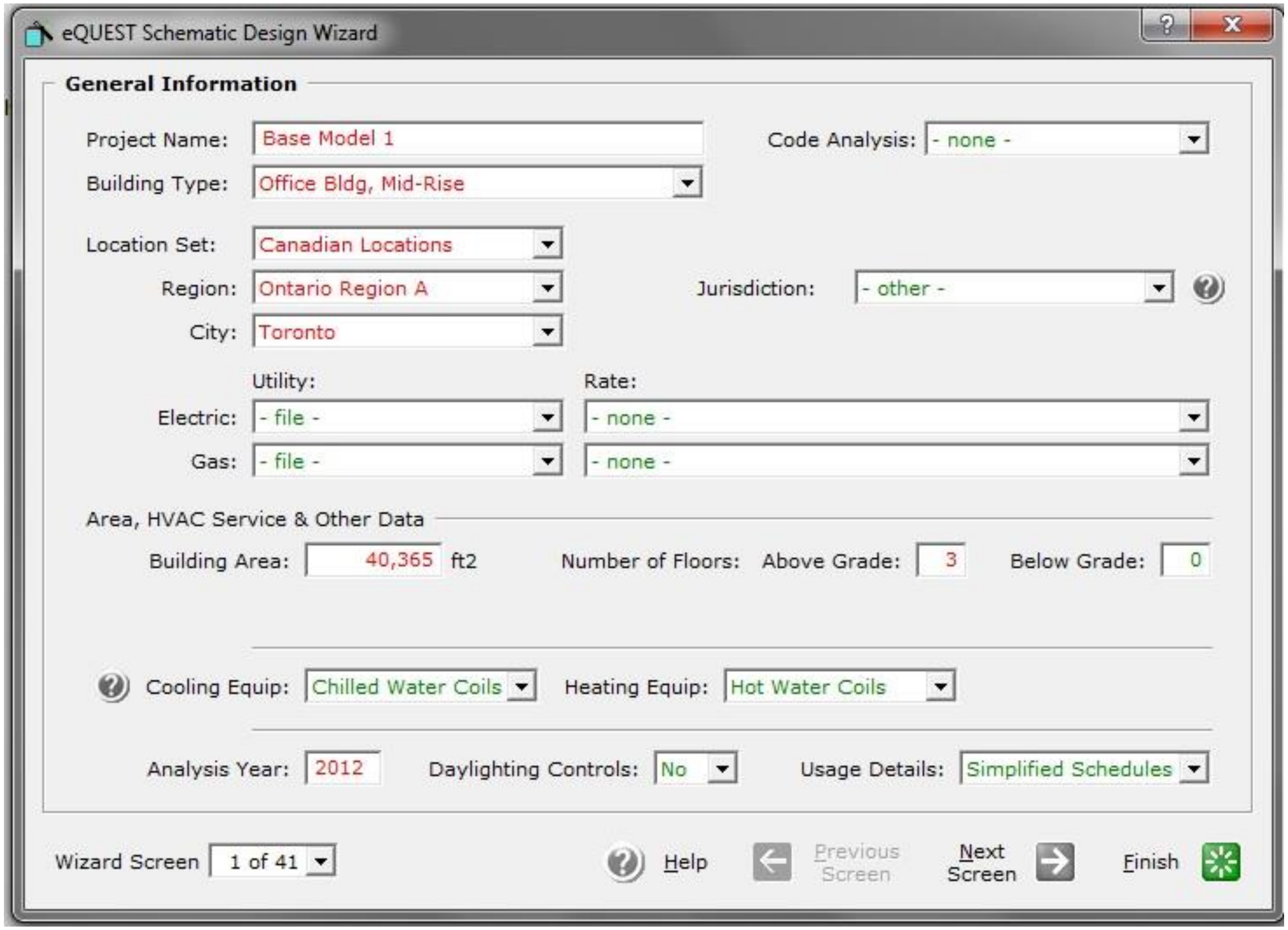
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1			**Load: Wall**												
2										**Heat Transfer (W)**					
3											**Conective**	**Radiative**			
4	**Month**	**Day**	**Hour**	**Conductive, North (W)**	**Conductive, East (W)**	**Conductive, South (W)**	**Conductive, West (W)**	**Overall Conductiion (W)**	**CTS Wall (%)**	**Total After CTS (W)**	**54%**	**46%**	**Nonsolar RTS**	**Radiation Load (W)**	**Total Load, Wall (W)**
29	1	1	1	-3442	-1721	-3442	-1721	-10326	2%	-10248	-5534	-4714	49%	-4770	-10305
30	1	1	2	-3726	-1863	-3726	-1863	-11178	2%	-10317	-5571	-4746	17%	-4777	-10349
31	1	1	3	-3896	-1948	-3896	-1948	-11689	2%	-10398	-5615	-4783	9%	-4795	-10410
32	1	1	4	-4067	-2033	-4067	-2033	-12201	3%	-10471	-5654	-4817	5%	-4816	-10470
33	1	1	5	-4124	-2062	-4124	-2062	-12371	5%	-10539	-5691	-4848	3%	-4836	-10527
34	1	1	6	-4237	-2119	-4237	-2119	-12712	6%	-10597	-5722	-4874	2%	-4855	-10577
35	1	1	7	-4124	-2062	-4124	-2062	-12371	7%	-10677	-5766	-4911	2%	-4878	-10643
36	1	1	8	-4058	-2023	-4050	-2029	-12160	7%	-10778	-5820	-4958	1%	-4907	-10727
37	1	1	9	-4005	-1940	-3884	-2003	-11832	7%	-10908	-5890	-5018	1%	-4947	-10837
38	1	1	10	-3717	-1648	-2985	-1859	-10209	7%	-11023	-5953	-5071	1%	-4988	-10941
39	1	1	11	-3560	-1559	-1727	-1780	-8626	6%	-11145	-6018	-5127	1%	-5032	-11051
40	1	1	12	-3502	-1655	-428	-1739	-7324	6%	-11209	-6053	-5156	1%	-5066	-11119
41	1	1	13	-3570	-1768	-1342	-1696	-8377	5%	-11263	-6082	-5181	1%	-5095	-11177
42	1	1	14	-3153	-1576	-1379	-1349	-7456	5%	-11220	-6059	-5161	1%	-5100	-11159
43	1	1	15	-3139	-1570	-2485	-1363	-8557	5%	-11103	-5996	-5107	1%	-5081	-11077
44	1	1	16	-3147	-1573	-3023	-1503	-9245	4%	-10936	-5906	-5031	1%	-5041	-10947
45	1	1	17	-3348	-1674	-3322	-1651	-9995	4%	-10743	-5801	-4942	1%	-4985	-10787
46	1	1	18	-3499	-1749	-3499	-1749	-10497	3%	-10547	-5696	-4852	1%	-4921	-10617
47	1	1	19	-3669	-1835	-3669	-1835	-11008	3%	-10377	-5603	-4773	1%	-4858	-10462
48	1	1	20	-3783	-1891	-3783	-1891	-11349	3%	-10242	-5531	-4711	1%	-4802	-10333
49	1	1	21	-3783	-1891	-3783	-1891	-11349	3%	-10154	-5483	-4671	0%	-4759	-10243
50	1	1	22	-3783	-1891	-3783	-1891	-11349	2%	-10139	-5475	-4664	0%	-4737	-10212
51	1	1	23	-3840	-1920	-3840	-1920	-11519	2%	-10146	-5479	-4667	0%	-4727	-10206
52	1	1	24	-3896	-1948	-3896	-1948	-11689	1%	-10208	-5512	-4696	0%	-4735	-10248

24-hour load calculation for walls

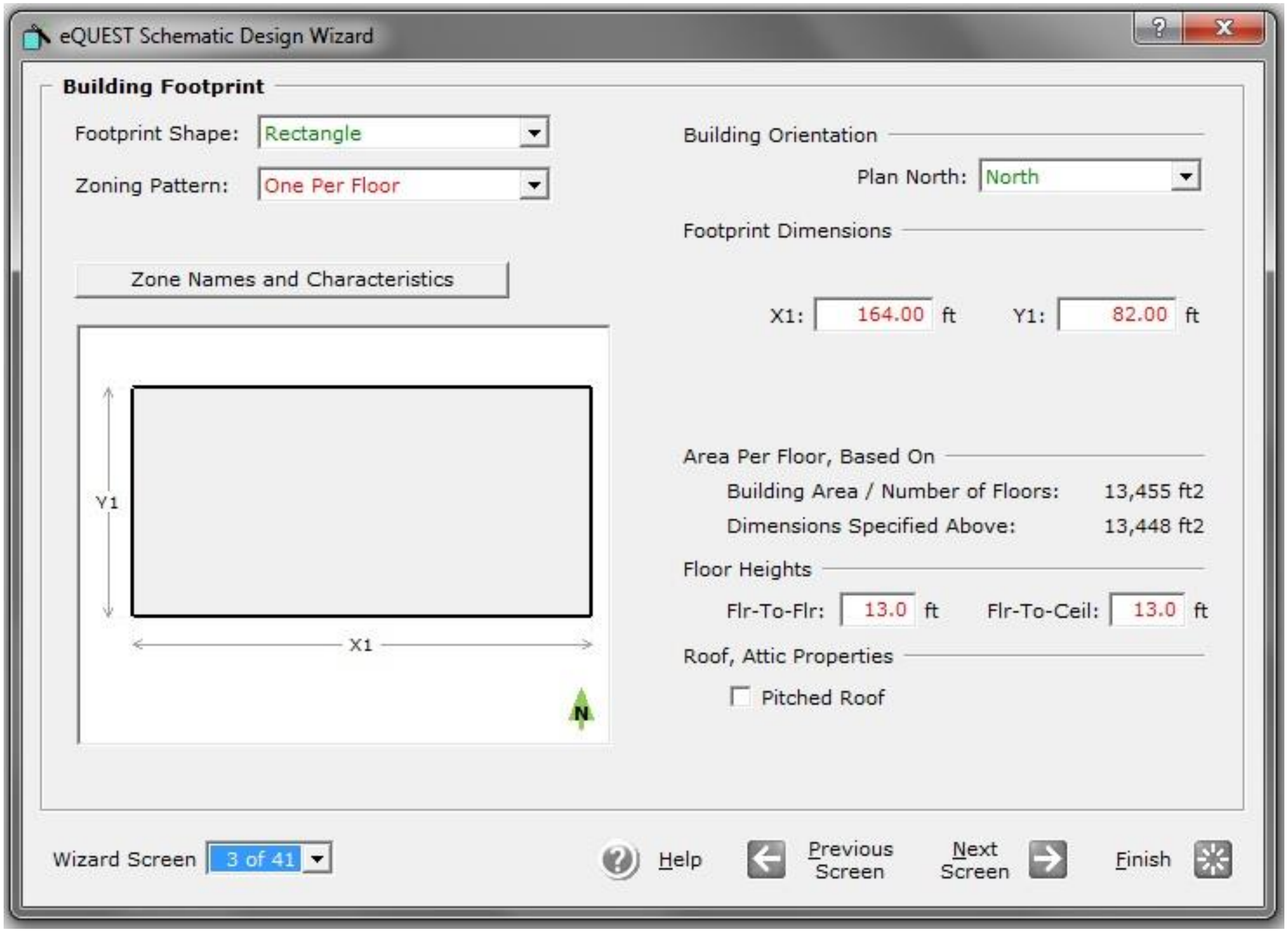
	A	B	C	D	E	F	G	H	I	J	K
1			**Load: Roof**								
2						**Heat Transfer (W)**					
3							**Conective**	**Radiative**			
4	**Month**	**Day**	**Hour**	**Conduction, Roof (W)**	**CTS Roof (%)**	**Total After CTS (W)**	**54%**	**46%**	**Nonsolar RTS**	**Radiation Load (W)**	**Total Load, Roof (W)**
29	1	1	1	-13372	2%	-13888	-7500	-6389	49%	-6755	-14254
30	1	1	2	-14358	2%	-13929	-7522	-6407	17%	-6654	-14175
31	1	1	3	-14949	3%	-13943	-7529	-6414	9%	-6600	-14129
32	1	1	4	-15541	4%	-13973	-7545	-6428	5%	-6575	-14121
33	1	1	5	-15738	5%	-14001	-7561	-6441	3%	-6563	-14124
34	1	1	6	-16133	6%	-14039	-7581	-6458	2%	-6559	-14140
35	1	1	7	-15738	6%	-14084	-7605	-6479	2%	-6557	-14162
36	1	1	8	-15512	6%	-14158	-7646	-6513	1%	-6569	-14215
37	1	1	9	-15360	6%	-14240	-7690	-6550	1%	-6586	-14276
38	1	1	10	-14166	6%	-14325	-7735	-6589	1%	-6606	-14342
39	1	1	11	-12979	6%	-14405	-7779	-6626	1%	-6628	-14406
40	1	1	12	-12170	5%	-14468	-7813	-6655	1%	-6647	-14459
41	1	1	13	-12972	5%	-14501	-7831	-6670	1%	-6659	-14490
42	1	1	14	-11430	5%	-14482	-7820	-6662	1%	-6658	-14479
43	1	1	15	-12113	4%	-14447	-7801	-6645	1%	-6649	-14450
44	1	1	16	-12372	4%	-14365	-7757	-6608	1%	-6626	-14383
45	1	1	17	-13058	4%	-14258	-7699	-6559	1%	-6591	-14290
46	1	1	18	-13569	4%	-14143	-7637	-6506	1%	-6550	-14187
47	1	1	19	-14161	3%	-14041	-7582	-6459	1%	-6507	-14089
48	1	1	20	-14555	3%	-13948	-7532	-6416	1%	-6466	-13998
49	1	1	21	-14555	3%	-13885	-7498	-6387	0%	-6438	-13936
50	1	1	22	-14555	3%	-13851	-7479	-6371	0%	-6418	-13897
51	1	1	23	-14752	3%	-13837	-7472	-6365	0%	-6406	-13878
52	1	1	24	-14949	2%	-13849	-7478	-6371	0%	-6403	-13881

24-hour load calculation for roof

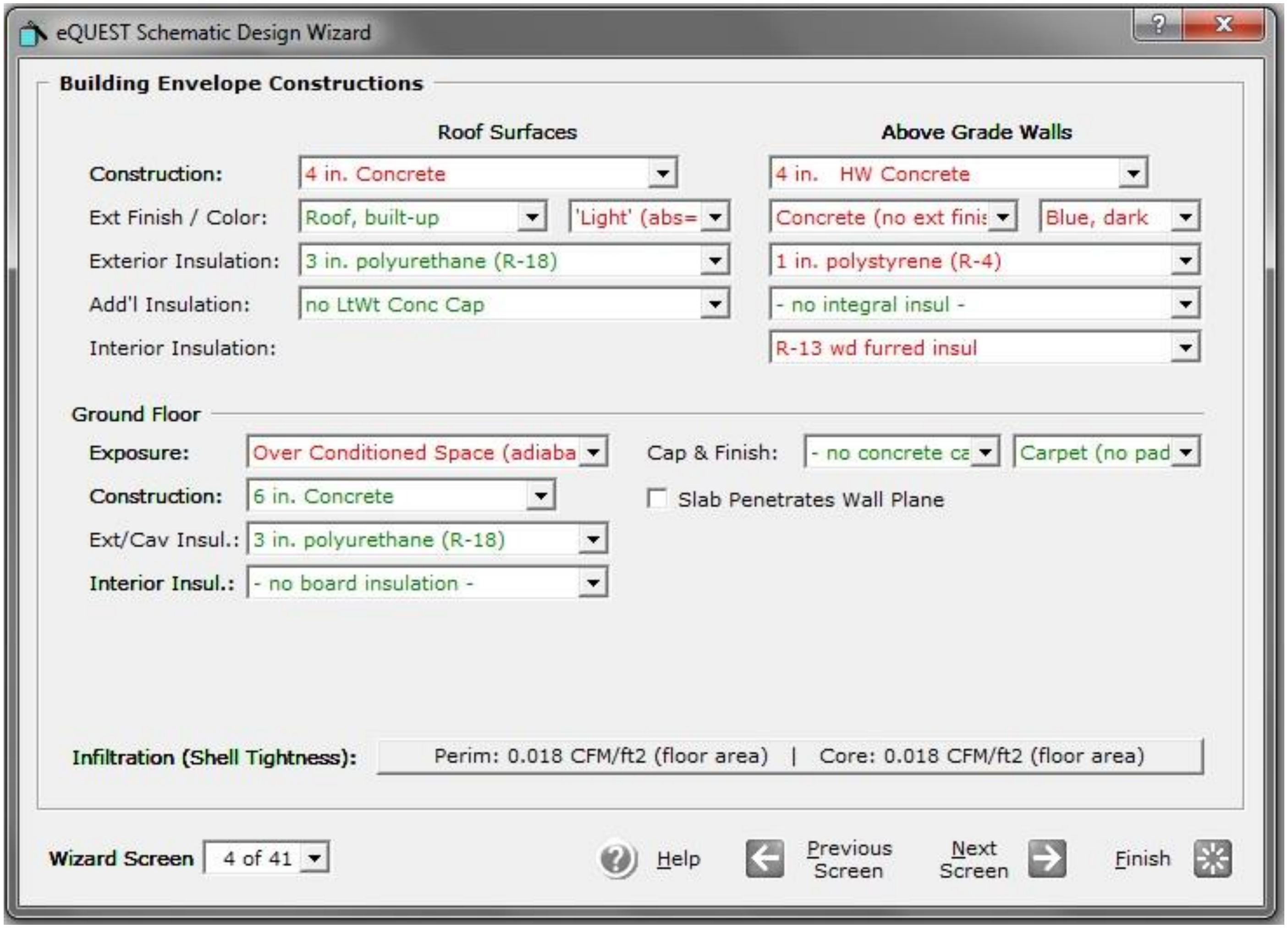
Appendix B – eQUEST Model



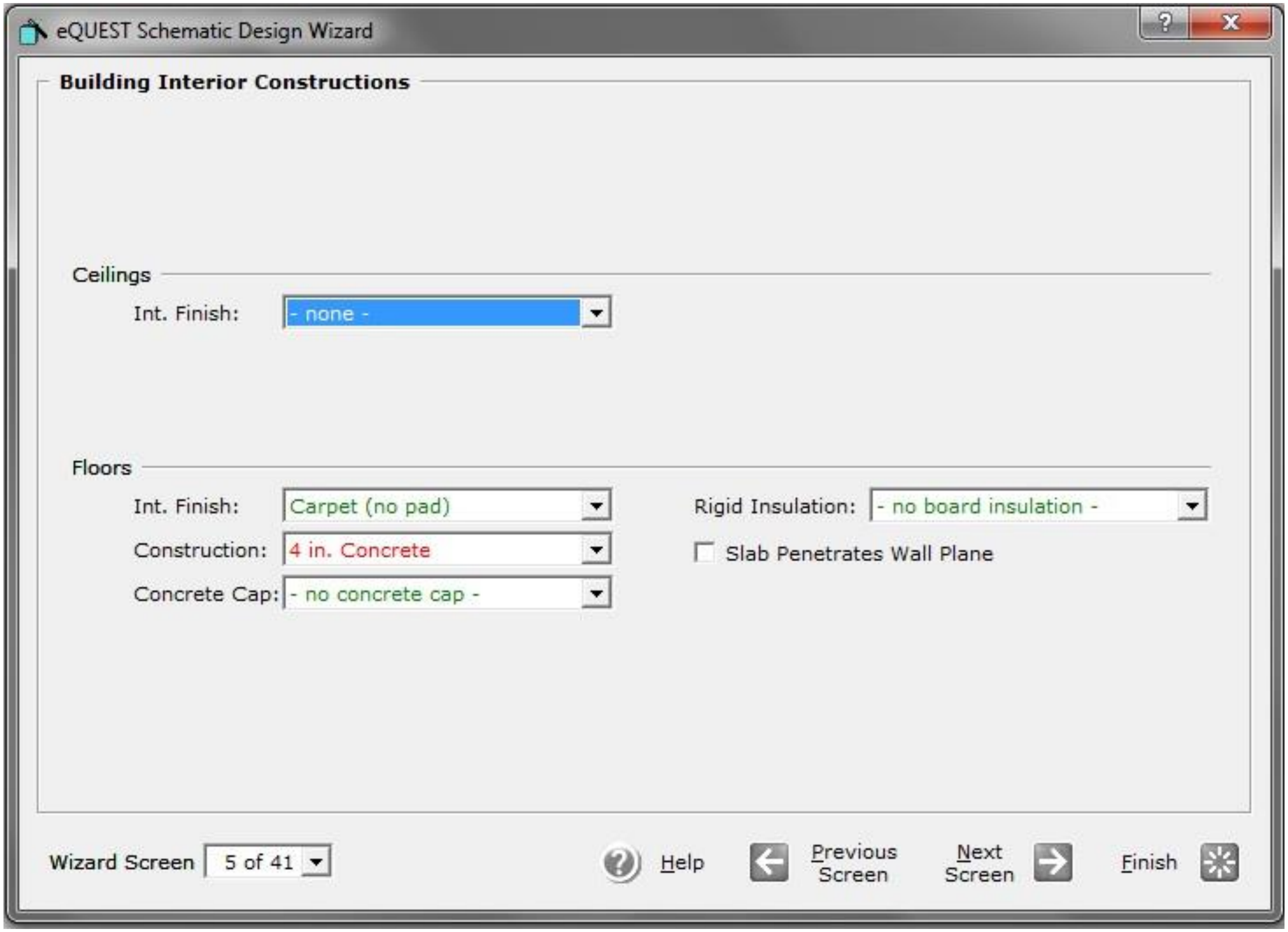
General building information of the eQUEST model



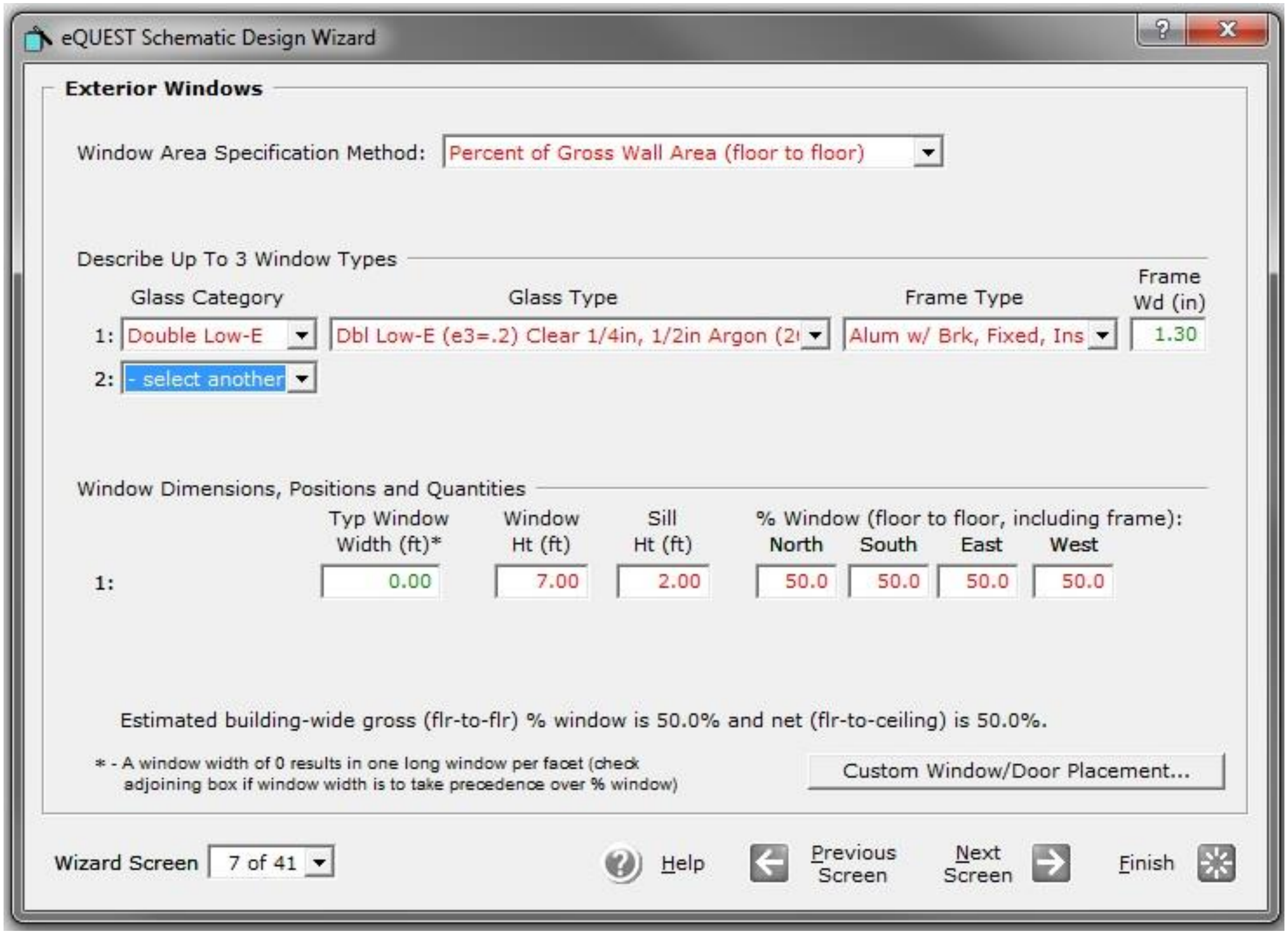
Building footprint of the eQUEST model



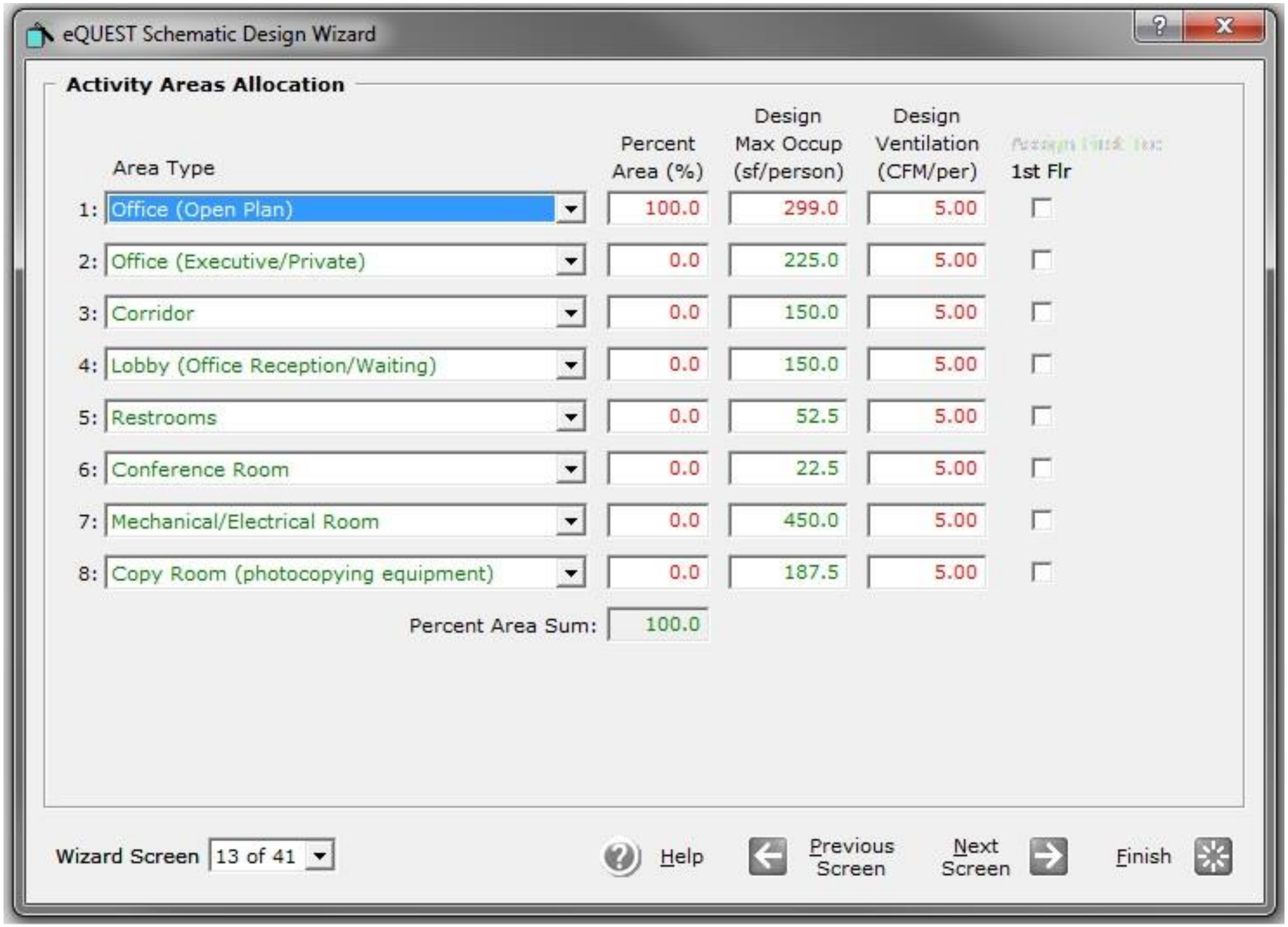
Building enclosure specification of the eQUEST model. The ground floor is set to adiabatic



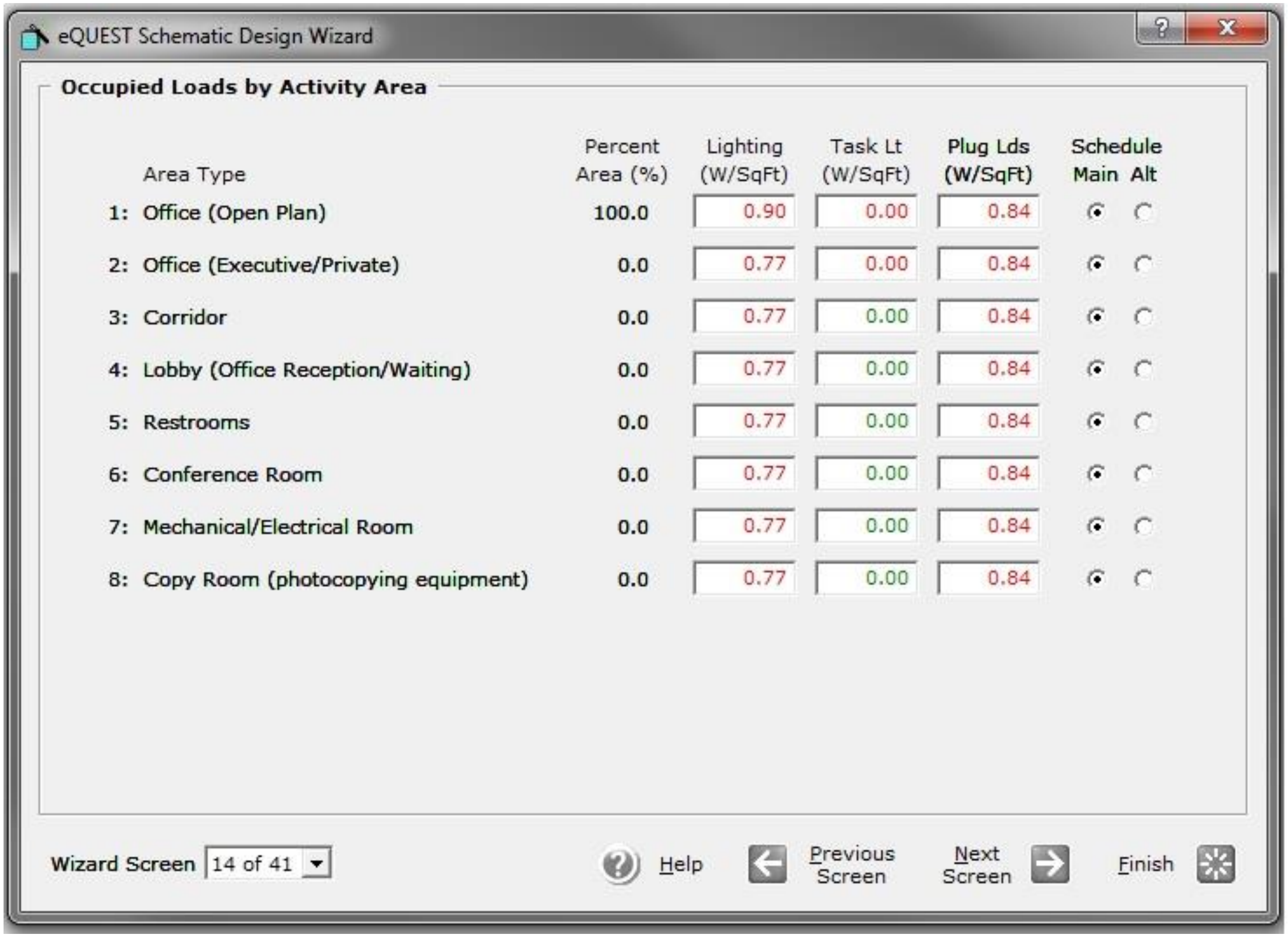
Interior building construction of the eQUEST model



Window specification and WWR of the eQUEST model

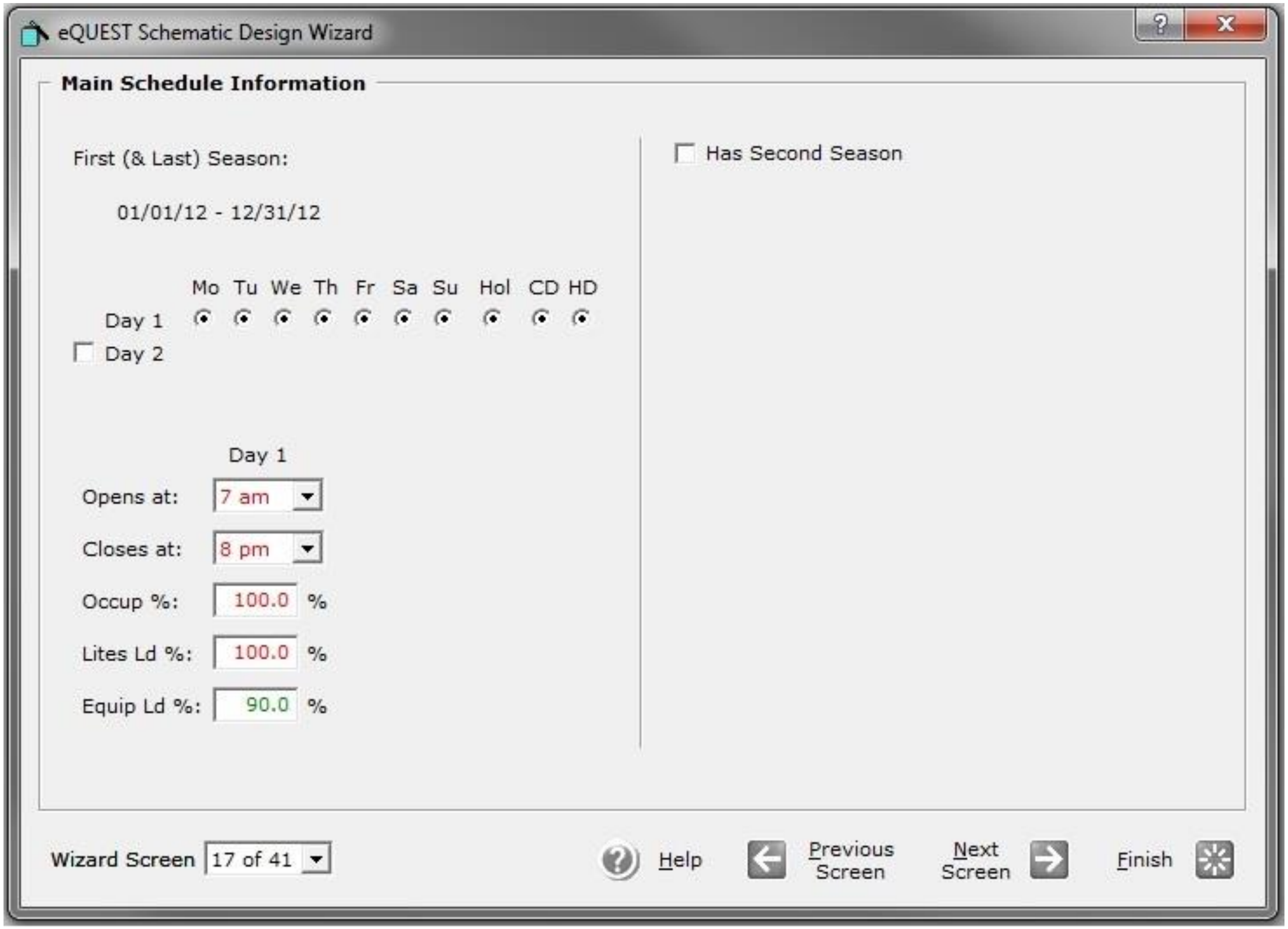


Occupant intensity of the eQUEST model



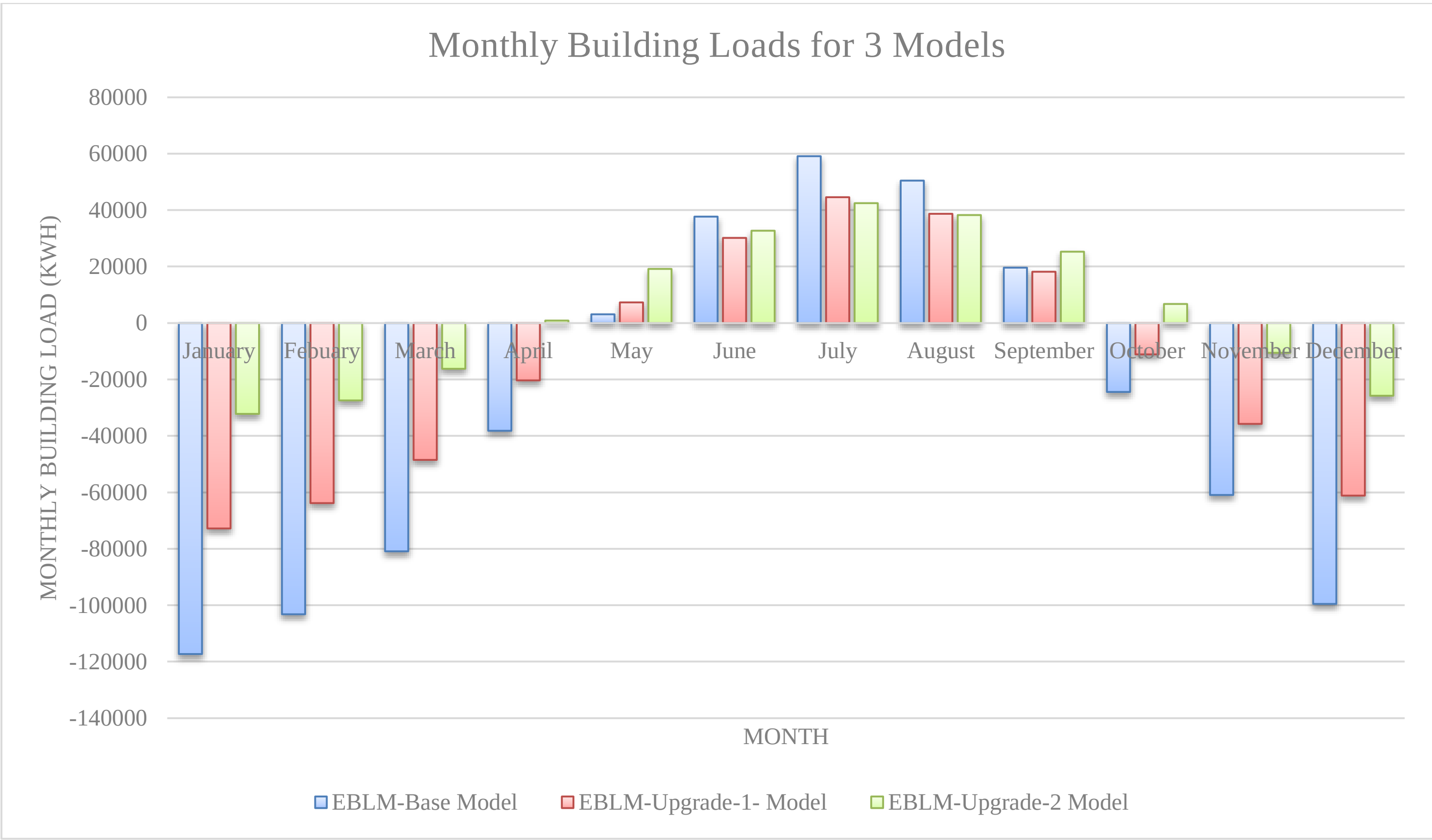
	Area Type	Percent Area (%)	Lighting (W/SqFt)	Task Lt (W/SqFt)	Plug Lds (W/SqFt)	Schedule Main	Schedule Alt
1:	Office (Open Plan)	100.0	0.90	0.00	0.84	●	○
2:	Office (Executive/Private)	0.0	0.77	0.00	0.84	●	○
3:	Corridor	0.0	0.77	0.00	0.84	●	○
4:	Lobby (Office Reception/Waiting)	0.0	0.77	0.00	0.84	●	○
5:	Restrooms	0.0	0.77	0.00	0.84	●	○
6:	Conference Room	0.0	0.77	0.00	0.84	●	○
7:	Mechanical/Electrical Room	0.0	0.77	0.00	0.84	●	○
8:	Copy Room (photocopying equipment)	0.0	0.77	0.00	0.84	●	○

Lighting power density and plug load of the eQUEST model



Operating schedule of the eQUEST model

Appendix C – Simulation Results



Monthly building loads for three models (Bars for each month from left to right: Base Model, High-performance Model, and Best-In-Class Model)

Monthly Building Loads Summary (Fixed Shading at 45 Slat Angle)	EBLM-High-performance Model-no Shade	EBLM-High-performance Model-Indoor	EBLM-High-performance Model-Interstitial	EBLM-High-performance Model-Outdoor
	Total Load (MWh)	**Total Load (MWh)**	**Total Load (MWh)**	**Total Load (MWh)**
January	-73	-74	-76	-78
February	-64	-65	-67	-69
March	-48	-50	-52	-55
April	-20	-22	-24	-27
May	7	6	3	-1
June	30	29	26	22
July	45	43	40	36
August	39	37	35	31
September	18	17	14	10
October	-11	-12	-15	-18
November	-36	-36	-37	-39
December	-61	-62	-63	-65

Monthly building loads of fixed shading systems at 45 degree of slat angle with different shading locations

Monthly Building Loads Summary - Operable Outdoor Temperature (Low SHGC)	EBLM-High-performance Model-no Shade	EBLM-High-performance Model-Indoor	EBLM-High-performance Model-Interstitial	EBLM-High-performance Model-Outdoor
	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)
January	-73	-73	-73	-74
February	-64	-64	-65	-65
March	-48	-50	-50	-51
April	-20	-23	-24	-25
May	7	3	2	0
June	30	25	24	23
July	45	39	38	36
August	39	34	33	31
September	18	13	12	10
October	-11	-15	-15	-16
November	-36	-37	-37	-38
December	-61	-61	-62	-62

Monthly building loads of the Low SHGC outdoor temperature control strategy

Monthly Building Loads Summary - Operable Outdoor Temperature (High SHGC)	**EBLM-High-performance Model-no Shade**	**EBLM-High-performance Model-Indoor**	**EBLM-High-performance Model-Interstitial**	**EBLM-High-performance Model-Outdoor**
	Total Load (MWh)	**Total Load (MWh)**	**Total Load (MWh)**	**Total Load (MWh)**
January	-73	-73	-71	-69
February	-64	-64	-62	-61
March	-48	-50	-48	-47
April	-20	-23	-22	-22
May	7	3	4	3
June	30	25	26	25
July	45	39	39	38
August	39	34	35	34
September	18	13	13	12
October	-11	-15	-14	-14
November	-36	-37	-37	-36
December	-61	-61	-60	-59

Monthly building loads of the high SHGC outdoor temperature control strategy

Monthly Building Loads Summary - Operable Solar Incident Intensity	**EBLM-High-performance Model-no Shade**	**EBLM-High-performance Model-Indoor**	**EBLM-High-performance Model-Interstitial**	**EBLM-High-performance Model-Outdoor**
	Total Load (MWh)	**Total Load (MWh)**	**Total Load (MWh)**	**Total Load (MWh)**
January	-73	-78	-78	-78
February	-64	-69	-69	-70
March	-48	-53	-54	-55
April	-20	-25	-25	-27
May	7	2	1	-1
June	30	26	25	23
July	45	39	38	36
August	39	34	34	32
September	18	13	12	11
October	-11	-16	-17	-18
November	-36	-38	-39	-39
December	-61	-64	-65	-65

Monthly building loads of the solar incident intensity control strategy

Monthly Building Loads Summary - Operable Combination of Outdoor Temperature and Solar Incident Intensity	EBLM-High-performance Model-no Shade	EBLM-High-performance Model-Indoor	EBLM-High-performance Model-Interstitial	EBLM-High-performance Model-Outdoor
	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)
January	-73	-73	-73	-74
February	-64	-64	-65	-65
March	-48	-50	-50	-51
April	-20	-23	-24	-25
May	7	3	2	0
June	30	26	25	23
July	45	39	38	36
August	39	34	34	32
September	18	13	12	11
October	-11	-14	-15	-16
November	-36	-37	-37	-38
December	-61	-61	-62	-62

Monthly building loads of the combination of outdoor temperature and solar incident intensity control strategy

Monthly Building Loads Summary-WWR	30 %	40 %	50 %	60 %
	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)	Total Load (MWh)
January	-69	-73	-77	-81
February	-60	-64	-67	-71
March	-46	-48	-51	-54
April	-19	-20	-21	-23
May	7	7	8	8
June	29	30	32	33
July	42	45	47	49
August	37	39	41	42
September	17	18	19	20
October	-10	-11	-12	-13
November	-33	-36	-38	-41
December	-57	-61	-65	-69

Monthly building loads of different WWR