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The Role of Thermal Simulation in Various Phases of Buildings' Life-Cycles in Improving Building Performances

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THE ROLE OF THERMAL SIMULATION IN VARIOUS PHASES OF BUILDINGS' LIFE-CYCLES IN IMPROVING BUILDING PERFORMANCES

By

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The role of thermal simulation in various phases of buildings' life-cycles in improving building performances

Master of Applied Science, 2010

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Building Science

Ryerson University

Abstract

Despite the proliferation of the usage of simulation programs in the conventional building design process, the use of thermal simulation programs in assessing energy and thermal performances of building designs are very limited. This thesis aims to investigate the role of thermal simulation programs in various phases of building projects' life cycles, and evaluate potential benefits these programs can bring. To illustrate the potential of these simulation programs, two case studies, one from the schematic design phase and the other from the post-occupancy phase, are presented. The thesis shows that, at each of these phases, thermal simulations can act as a feedback tool where performances of different strategies can be evaluated, which in turn allows energy conserving strategies to be recognized. The thesis also shows that, at the post-occupancy phase, conducting thermal simulation studies with existing buildings can also help highlight poor performances.

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1. Introduction

This thesis is concerned with the investigation of the role of thermal simulation programs in various phases of buildings' life-cycles, and the evaluation of potential benefits these programs can bring. It aims to provide designers with the knowledge necessary to change their accepted standard practices for building design and potentially increase the popularity of thermal simulation studies in various phases of buildings' life-cycles.

The energy and thermal performance of buildings is dependent on complex interactions between the mechanical, electrical, and structural systems, building operation and maintenance, and the environmental factors that the building is subjected to. One of the major challenges in building designs is to understand the interaction between the various building systems and also their associated implications on overall building performance. The challenge is further enhanced when designers try to incorporate novel and innovate design features into building designs. The complexity of physics phenomena and thermal behaviour of buildings often leads to difficulties in assessing the thermal and energy performance of building designs in professional practises.

With increasing complexity involved in building designs, the demand for the use of computational building performance evaluation and design support tools throughout the building design process is recognized. Tremendous amount of research and development has been done over the past three decades in developing computer simulation programs for use in building designs. The Building Energy Software Tools Directory (U. S. Department of Energy [US DOE], 2006) lists over 380 software for evaluating energy efficiency, performance of renewable energy systems, and sustainability in buildings, as well as verifying designs in fulfilling the requirements as specified by codes or standards for various building systems. These programs allow building designers to evaluate the impact of design on the various performance mandates, such as thermal, structural, acoustic, and lighting. To some extent, these programs have been able to replace expensive and time consuming field tests and provide comprehensive evaluations of the different building systems to provide confidence in designs (Hien et al., 2000).

Of the 380 software listed in the Building Energy Software Tools Directory, whole building energy simulation programs, or thermal simulation programs can assess the energy performances of building designs as well as providing insights into the indoor environmental conditions. Although a number of sophisticated thermal simulation programs have been developed in recent years, the usage of these programs in the building construction industry has been quite limited to verifying designs for codes or standards compliances, and not so much on utilizing these programs as an active design tool. Most buildings constructed nowadays are still constructed without properly accounting for their associated energy consumptions (Hien, 2000; Hobbs et al., 2003). These programs can be used to evaluate different design strategies in identifying and assessing individual or integrated design ideas in reducing operational energy consumptions. However, these programs have predominantly been used by academia and privately- and publicly- funded research centers, and except for buildings that follow green building rating standards such as Leadership in Energy and Environmental Design (LEED), which requires the use of thermal simulation to demonstrate certain level of energy efficiency, there has been little effort by the building construction industry to incorporate detailed building energy analysis as a standard part of the building design process (Hien, 2000).

1.1 Background

Recent concerns about climate change have placed new emphasis on and increased demand for low-energy buildings. The operation of buildings accounts for approximately 40% of the total energy consumption in the world (International Energy Agency [IEA], 2008) and in developed countries like Canada and USA, up to 60% of this energy is used for space heating and air conditioning (U.S. Energy Information Agency, 2005; Natural Resources Canada [NRCan], 2006). In the year of 2006, the buildings sector in Canada contributed to 27% of the national carbon dioxide (CO_2) emissions (NRCan, 2006) and thus buildings are primary targets for future carbon emissions reductions. Closely related to the energy efficiency of buildings, is the energy that needs to be consumed by mechanical systems to provide thermally comfortable environments for occupants. Nowadays, most people in North America spend approximately 90% of their time indoors, and as much as 80% of which are spent in their residences (Klepeis et al., 2001). Most of the time, the residences have to rely on the mechanical systems to provide a desired indoor environmental quality (IEQ). For the past decades, enormous research have been dedicated to establish better understandings on the indoor environment and some studies have shown that poor management of IEQ would lead to health hazards such as sick building syndrome (SBS) and reduced productivity (Milton et al., 2000; Seppanen & Fisk 1998; Chao et al., 2003; Li & Lian, 2009). The ability of HVAC systems to provide and maintain a comfortable and healthy indoor environment in an energy-efficient manner is crucial.

With growing environmental and energy consciousness, consuming energy more efficiently is a priority. As 40 % of the world’s primary energy consumption is used for building operations, any improvement in building energy usage will contribute to the global energy conservation effort. Together with the increasing concerns of poor IEQ to health conditions, exploring ways in conserving energy as well as improving comfort in buildings are of top priorities. Incorporation of thermal simulation studies in various phases of buildings' life-cycles could potentially contribute to reducing energy consumptions and improving thermal comfort in buildings.

To illustrate the potential of using thermal simulation programs in different phases of the life-cycles of buildings, it is necessary to first define the different phases in the context of this study.

The life-cycle of a building generally involves the following phases: pre-design, schematic design, design development, construction documents, construction, and operation/post-occupancy. The exact nature of these phases varies with projects and design teams, but there exist some general consistencies.

The first phase of design is where the project is conceptualized and the intention is elaborated. The pre-design phase involves the development of the brief for the project. Outline of requirements are elaborated and major design decisions are made. The next phase, the schematic design phase is where the design brief is fully developed with preliminary design drawings and relationships among different components developed for review. The objective of this phase is to develop a clearly defined and feasible concept, and the project proceeds to the next phase when the owner or client approves the concepts put forward by the design team. In the design development phase, schematic design decisions are validated. In the conventional process, architectural drawings are passed onto different engineering professions, and all structural, mechanical, and electrical systems are assessed for their expected performance, and individual systems are designed and optimized separately. Simulation programs are used in verifying individual designs for code compliance. After design decisions are validated, details are developed and specific equipments are selected at the design development phase. Subsequently, the project enters the construction document phase. Construction drawings, specifications, and related tendering and bidding documents are prepared and conveyed to contractors. Afterwards, during the construction phase, the main design plans are realized and commissioning takes place in some projects during this phase. At last, the building is occupied and operated. On most projects, design teams have no or just minimal interaction with the occupied building. The building will then be operated and inhabited for a prolong period of time before the building proceeds with deconstruction. The conventional project delivery process is a linear process where design phases are carried out in series (Fig. 1). Also, occupants generally do not have the opportunity to be involved in providing feedback throughout the entire life-cycle of the building.

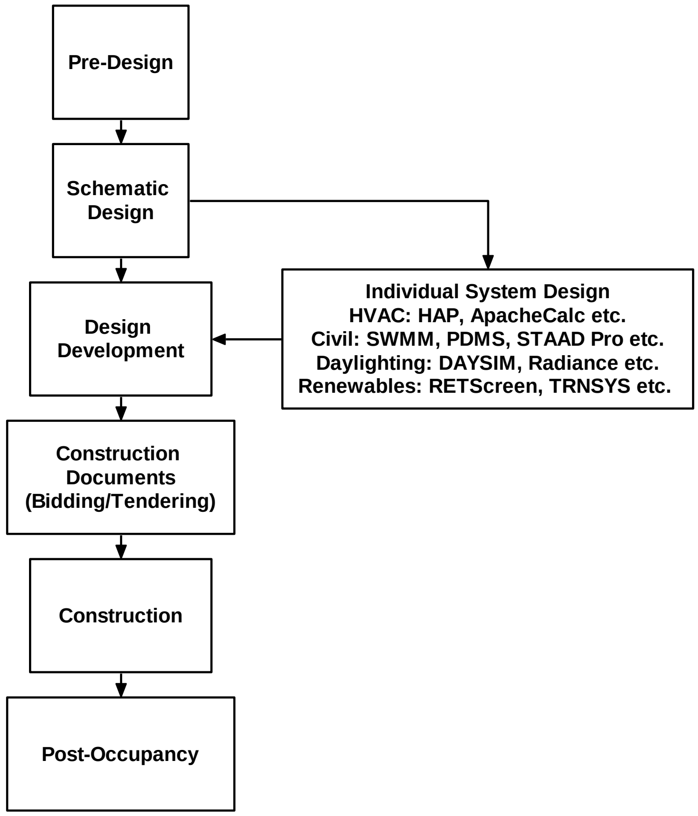

Figure 1 – Conventional building's life-cycle

The conventional building's life-cycle lacked opportunities to explore energy conserving design strategies. Buildings are generally designed, constructed, and operated without being subjected to comprehensive energy analysis using computerized thermal simulation programs. To provide substantial improvements to energy consumption and, potentially, comfort levels, a number of thermal simulation programs can be used to predict a building's performance before and after it is built. Not only can these powerful predictive computer programs help evaluate individual design strategies, but they can also assess the collective performances of design strategies. The process in identifying and evaluating different strategies often results as an iterative process where design ideas and concepts are exchanged between designers and engineers. Ideas put forward are applied to the thermal simulation model for performances evaluations, and modifications will proceed if necessary (Fig. 2). The thermal simulation model can be considered as a feedback tool where detailed energy and thermal analyses on different strategies are evaluated. Design decisions can then be based on these analyses for the final building design.

During the schematic design phase, energy conserving strategies can be proposed and evaluated using thermal simulation models. This process can be in conjunction with an integrated design process (IDP). IDP aims to maximize the opportunity for integration and collaboration between building systems early in the design process.

During the post-occupancy phase, comprehensive evaluations are crucial in identifying whether the final building design has met its original design intent. Application of thermal simulation at this phase could help identify and assess the potential deficiencies in the existing building, and in turn evaluate strategies to improve performances. Prior to conducting thermal simulation studies during the post-occupancy phase, post-occupancy evaluation (POE) is required to first acquire valuable feedback from occupants . POE is a feedback tool where it helps identify if design intents, specifically those related to thermal comfort and energy consumptions, have been met.

Thesis will focus on the role of thermal simulation programs in improving building performances during the schematic design and post-occupancy phases. It is however important to note that, in addition to these two phases, thermal simulation may be applied to other phases in improving building performances. For instance, in the pre-design phase, thermal simulation can be applied to predict energy performance of various design options that concerns with the different orientation, massing, and structure of the building. In the post-occupancy phase, on top of employing thermal simulation as a diagnosis tool, thermal simulation can also be used in help certifying energy performances, and in turn contribute to potential building energy labelling programs (ASHRAE, 2009).

Thesis aims to focus on the residential sector as it represents approximately 60% of the total energy usage in buildings in Canada (NRCan, 2006). As commercial and institutional buildings have different design principles, building functions, and occupancy schedules than residential buildings, findings of this thesis might not be directly applicable to the other two types of buildings.

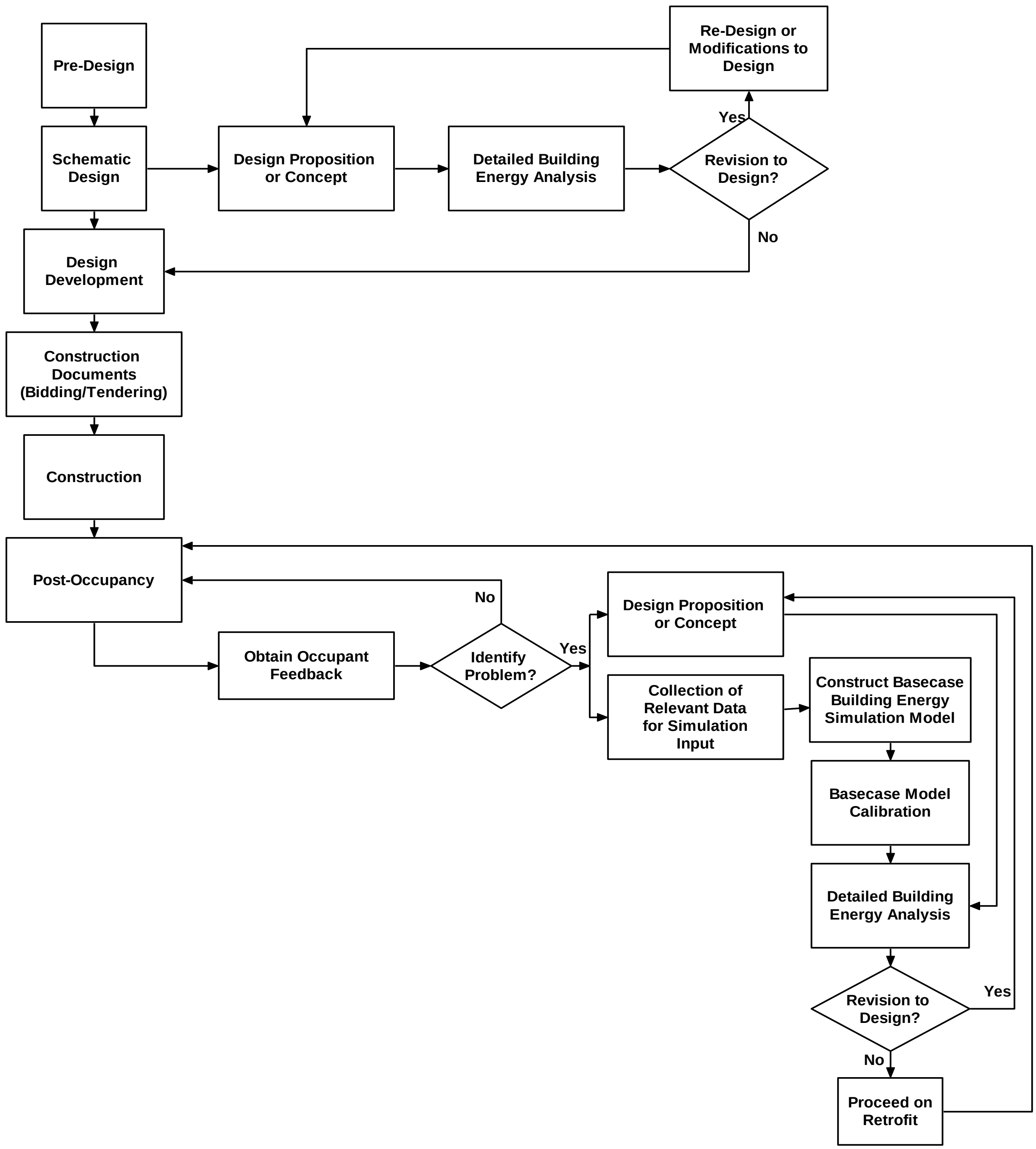

Figure 2 - Incorporation of thermal simulation studies in building's life-cycle

1.2 Research objectives

The objective of this thesis is to demonstrate the potential of conducting thermal simulation studies in reducing energy consumptions and improving thermal comfort levels in various phases of buildings' life-cycles. This will be demonstrated through two research projects.

The first research project focuses on the design of a low-energy envelope system for a multi-unit residential building (MURB) to be located in downtown Toronto. The MURB was under schematic design at the time when the research project was undertaken. As part of the research project, detailed building energy analysis was conducted with a sophisticated thermal simulation program, EnergyPlus (EnergyPlus, 2009) to evaluate the performances of different low-energy envelope strategies. It shows that when designing buildings in the schematic design phase, it is necessary to perform thermal simulations to evaluate the energy savings of potential improvements to the envelope system.

The second research project demonstrates the use of thermal simulation programs for the modeling of an existing single-detached house during the post-occupancy phase. As part of the second project, a POE was conducted in the form of a full-scale survey to identify deficiencies in systems being built today in this type of buildings. The research project illustrates the importance of employing thermal simulation studies alongside on-site measurements in establishing a realistic model to help identify systematic problems in existing buildings. Subsequently, the model can be used to evaluate alternatives for identifying improvements to thermal and energy performances.

1.3 Methodologies

For both case studies, DesignBuilder v. 2.0.4.002 was employed to generate the geometric details. Models were then exported to EnergyPlus in specifying Heating, Ventilating, and Air Conditioning (HVAC) equipments and systems, schedules, sizing, and internal load, etc. Simulations were performed directly from EnergyPlus v.3.1.0.027. There are many simulation programs available nowadays for thermal simulation such as EnergyPlus, ESP-r, eQuest, HAP, and TRACE, etc. EnergyPlus is a modular, structured software tool based on the most popular features and capabilities of BLAST and DOE-2.1E (Crawley et al., 2005). DesignBuilder is a graphical user interface to the EnergyPlus simulation tool.

The two research projects were taken place with buildings located in Toronto, Ontario. The climate in Toronto is marked by cold winters and relatively warm summers. According to the Environment Canada (Environment Canada, 2008) historical data, the annual average outdoor temperature is 7.5^{o}C, and the warmest month is typically July with mean temperature of 20.8^{o}C. The coldest months are January and February, with mean temperatures -6.3 ^{o}C and -5.4^{o}C respectively. Heating Degree Days (HDD) is approximately 4000. International Weather for Energy Calculations (IWEC) and Canadian Weather for Energy Calculations (CWEC) climatic data for the nearest weather stations, Toronto Buttonville Airport and Toronto International Airport were used in thermal simulations for model calibration and simulations.

1.4 Thesis outline

This thesis has started with a review of the background on the modeling of building performance and its application. The research objectives and methodologies have been described. The remaining of this thesis is organized into four chapters as below:

Chapter 2 introduces the background knowledge and theory on thermal simulation programs and compares five thermal simulation programs commonly used in today's practise. Two of the five simulation programs are considered more sophisticated, namely EnergyPlus and ESP-r. These programs are more commonly used among academia and research groups due to its complexity and the large amount of input that is required. The rest of the simulation programs evaluated are commonly used in professional practices, namely eQuest, HAP, and TRACE. Subsequently, barriers in using these programs as a standard part of the building design process are elaborated.

Chapter 3 focuses on the benefits thermal simulation studies can bring to the final building design during the schematic design phase. The energy performance of a 12-storey MURB in Toronto under schematic design phase is investigated. First, the importance of conducting thermal simulation studies as part of an IDP is elaborated. Then an overview of the research on low-energy envelope designs in MURB will be presented, followed by the model parameters used to simulate the building. Results and discussions of the thermal simulation study are then presented.

Chapter 4 illustrates the potential benefits in incorporating thermal simulation studies in the post-occupancy phase. The chapter starts off with elaborating the benefits and importance of subjecting existing buildings to comprehensive evaluations. This is followed by a discussion of the results gathered from the POE conducted in low-rise residential buildings in Ontario, Canada. Model parameters used to simulate the building are presented, followed by a discussion of the model calibration and validation. Results and discussions of the thermal simulation study are then presented.

Chapter 5 concludes this thesis and points out the future work.

2. Overview of Building Thermal Simulation

2.0 Introduction

There are many aspects to consider concerning energy consumption in building designs, including HVAC system design, building envelope design, lighting design, and maintenance of IEQ, etc. Design tools that could take all the above aspects into account are essential in generating energy-efficient building designs. Thermal simulation programs have demonstrated to be an effective design tool for analyzing design strategies and helping design teams in better understanding the complex behaviour of building energy consumption. Since the inception of simulation programs in the 1970's, numerous efforts have been put into the development of the techniques and applications of thermal simulation programs (Ellis & Matthews, 2002). During this period, a number of studies have been conducted to contrast the vast number of simulation programs available worldwide, analyze the trends and needs for these design tools to become more popular in the conventional design process, or validating the accuracy of the programs (Hall & Deringer, 1989; Rousseau & Matthews, 1993; Judkoff & Neymark, 1995; McElroy & Clarke, 1999; Hien et al., 2000, Ellis & Matthews, 2002; Hobbs et al., 2003; Crawley et al., 2005).

2.1 The Theory

The fundamentals of thermal simulation programs are based on the traditional methods of load and energy calculations in HVAC design. Depending on the simulation programs' area of specialisation and level of detail, different modelling approaches and solution techniques can be used. They also vary in complexity and accuracy, from simple steady state calculations to finite difference methods (Ellis & Matthews, 2002). Although the method and capabilities may vary with different programs, the general approach to the energy simulation task is similar (Fig. 3).

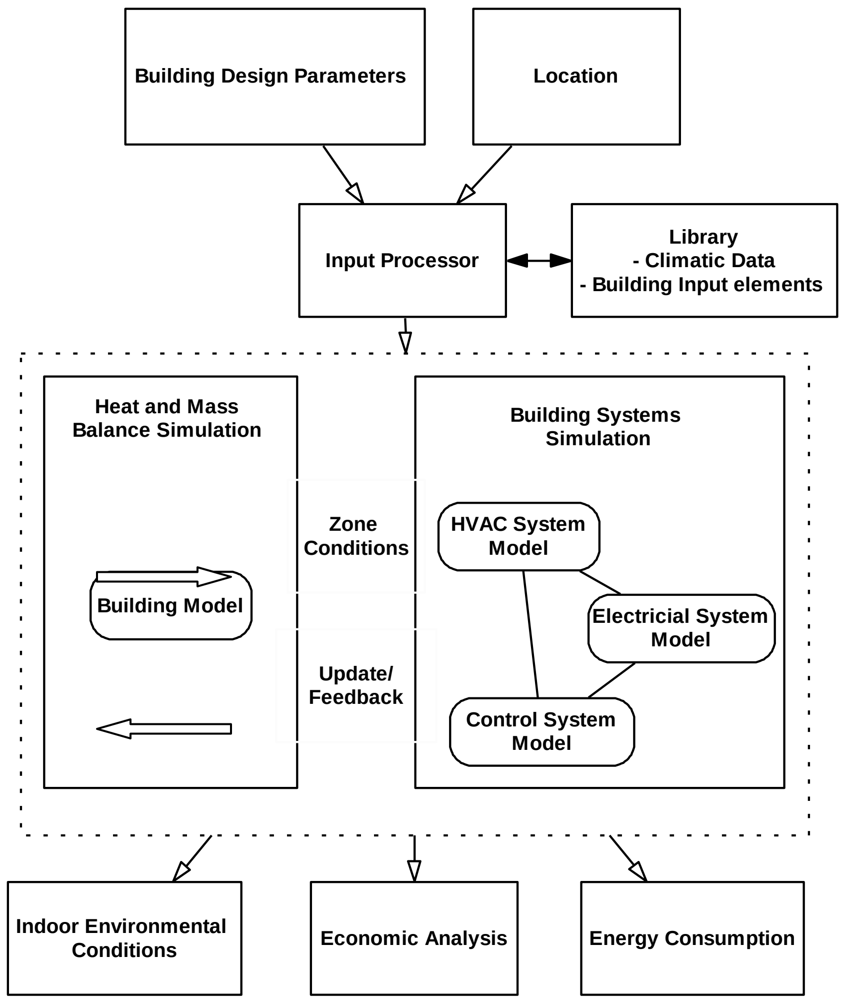

Figure 3 - Typical structure of thermal simulation (Clarke & Irving 1988; Hui, 1998; Crawley et al., 2001)

Thermal simulation programs require the user to specify the design parameters such as the envelope details, operational schedules, indoor environmental condition requirements, HVAC configurations, etc. and the boundary condition that the building is subjected to. The input from the user will then be fed into an input processor. The processor takes that data and interacts with a library that contains an array of building input elements including wall materials, glazing systems, HVAC equipment specifications, and climatic data, which typically consists of hourly values of outside dry-bulb temperature, wet-bulb temperature, atmospheric pressure, wind speed and direction, cloud cover, and solar radiation, etc. The formatted input data will then be translated to the simulation environment.

In general, the simulation environment has at least two basic components – a heat and mass balance simulation module and a building systems simulation module. The heat and mass balance simulation module is responsible for thermal zone calculations, which calculates the sensible and latent components of the heating and cooling load for each user-designated zone in the building, and conveys data to and from the building systems simulation modules by air-heat balance or surface-heat balance computations. The common assumption in the heat and mass balance simulation module is that the room temperature is uniformly distributed across each user-designated zone. And depending on the simulation program's level of detail, this module can be further subdivided into sub-modules that can deal with day-lighting illumination and day-lighting control, shading and reflection from neighbouring buildings and structures, complex fenestration systems, and renewable energy systems.

The building systems simulation module handle HVAC plant and zone equipments such as coils, boilers, chillers, pumps, fans, and other equipments, and electrical equipments such as lighting and photovoltaic modules, etc. It uses the data calculated by the heat and mass balance simulation module and estimates the energy requirements of the building systems to meet the required loads by taking into account outside air requirements, hours of equipment operation, equipment control strategies, and thermostat set-points, etc. Data are then fed into the heat and mass balance simulation module to update the zone environmental conditions. Subsequently, the user can request various outputs as desired. The outputs can be building energy consumptions, peak demands, indoor environmental conditions, greenhouse gas emissions, and economic analyses, etc.

Some studies showed disconnections between energy savings predicted through energy modeling and those actually realized (Gonchar, 2008; Mendon, 2009). It is important to note that the purpose of thermal simulation is to provide a uniform and consistent mean of comparing the energy performances of different strategies. The actual performance of the building will be dependent on the following, but not limited to: actual weather conditions, quality of installation, proper operation and maintenance of mechanical equipments, and occupant behaviours. For instance, using weather files from different periods, Radhi (2009) reported a difference of up to 14% from simulation results with present and historical weather data. Seligman et al., (1977), Filippin et al. (2005), and Bahaj & James (2007) all reported that behavioural aspects, particularly on the control of heating and cooling equipments and window openings, play a significant role in energy consumption in residential buildings.

2.2 Capabilities of Selected Simulation Programs

There are many thermal simulation programs available nowadays for evaluating building energy and thermal performances. It is believed that thermal simulation is a powerful, analytical method for building energy research. The use of these programs has demonstrated to be able to contribute to substantial improvements in energy efficiency and thermal comfort level in actual building designs. A comprehensive list of the thermal simulation programs used worldwide is located at the U.S. Department of Energy's Building Energy Software Tools Directory (U.S. DOE, 2006). Crawley et al. (2005) conducted a comprehensive comparative study on the most popular thermal simulation programs to date.

Five simulation programs namely EnergyPlus, ESP-r, eQuest, HAP, and TRACE were reviewed and compared (Table 1). The information provided in Table 1 is based on vendor supplied information and the previously published report by Crawley et al. (2005).The main users for three of the five simulation programs, namely eQuest, HAP, and TRACE are engineers and building design practitioners. These programs generally feature graphical user interfaces that are relatively simple, straightforward, and intuitive to use when compared to more powerful and comprehensive simulation programs like EnergyPlus and ESP-r.

In this study EnergyPlus was selected as the thermal simulation tool because of the program's versatility and flexibility in simulation inputs and outputs, as well as the program's ability to simulate building performances that adhere closely to actual performances. EnergyPlus has been tested against the IEA BESTest building load and HVAC tests (Henninger et al., 2003). EnergyPlus provides an integrated simulation environment with simultaneous loads and systems for accurate energy consumption, temperature, and thermal comfort prediction. The input of EnergyPlus is text based and a user interface to EnergyPlus, DesignBuilder was used to create and edit building geometries in this study.

Table 1 - Comparison between commonly used simulation programs

	EnergyPlus	ESP-r	eQuest	HAP	TRACE
Developer(s)	U.S. Department of Energy	Department of Mechanical Engineering, University of Strathclyde	U.S. Department of Energy, James J. Hirsch and Associates	Carrier Corporation	The Trane Company
Graphical User Interface	-	-	X	X	X
Simulation solutions	Simultaneous loads	Simultaneous loads	Simultaneous loads	Simultaneous loads	Sequential loads without feedback
Iterative non-linear systems solution	X	X	-	X	X
Space temperature based on loads-systems feedback	X	X	-	X	X
Time step dynamically varies with solution transients	X	X	-	-	-
Complex geometric description	X	X	X	-	-
Building material moisture characteristics	X	X	-	-	-
Element conduction solution method	Transfer functions	Finite difference method	Transfer functions	Transfer functions	Transfer functions
Interior surface convection	X	X	-	-	-
Internal thermal mass	X	X	X	-	X
Surface conduction	2- and 3-D	2- and 3-D	1-D	1-D	1-D
Ground heat transfer	2- and 3-D	2- and 3-D	1-D	1-D	N/A
Human comfort prediction	X	X	-	-	-
Advanced fenestration	X	X	P	-	P
Natural Ventilation (Pressure and buoyancy driven)	X	X	P	-	-
Multi-zone air flow model	X	X	-	-	-
Weather data - International Weather for Energy Calculations	X	-	-	-	X
Weather data - Typical Meteorological Year	X	X	X	-	X
Complex economic models	X	-	X	X	X
Graphical report	-	X	X	X	P
HVAC system network diagramming	X	X	X	-	-
Validated with IEA Task 12	X	X	-	X	X
Validated with IEA Task 22	X	X	P	-	P

Abbreviations in the table: X - feature that is available and in common use

P - feature that is partially implemented

2.3 Barriers to the application of simulation programs

Despite the proliferation of many thermal simulation programs and their increasing usage for building design, their usage by design teams in the schematic design phase has been very limited. There exists a list of barriers that needs to be overcome before the application of thermal simulations can become more popular in the building design process (Mahdavi, 1998; Hien, 2000; Ellis, 2002).

Since the inception of thermal simulation programs, architects and design team members have found that some of these programs are complex in nature and are very difficult to use (Ellis, 2002). The usage of these simulation programs also requires the user to have an in-depth understanding of the underlying modelling principles and the operation parameters for various building systems.

Although sophisticated programs like ESP-r and EnergyPlus can usually better represent real-world complexities (Table 1), they are more likely to require excessive data input from the user (Hobbs et al., 2003). Design team members are usually overwhelmed by the amount of data required and have difficulties in gathering all the necessary inputs, especially during the initial design stages when certain parameters are nonexistent yet. As an alternative, the user might be subjected to making crude assumptions in some of the parameters and risk degrading the accuracy of the simulation results. Some simulation programs such as eQuest, HAP, and TRACE provide dynamic default values for some of the parameters to greatly reduce the complexity of the input requirements. However, this can lead to an over-reliance on the default values and rendering the user to have a much lower understanding on the parameters being used. This would adversely affect the quality of the simulation results as the simulated performances might be based on faulty assumptions.

The steep learning curves on certain programs prohibit designers to educate themselves with these advanced design tools (Ellis & Matthews, 2002). The time required to learn the program can be at times excessive, and some designers felt that the programs are not user-friendly and lack support from the software developers (Hien et al., 2000). As well, some designers felt that the usage of such simulation programs was beyond their scope of work and argued that these programs should be utilized only by specialist consultants, researchers, or suppliers. Their objective was to fulfill the requirement as specified by the codes of practise and thus the usage of complicated simulation programs was not essential.

In addition, building projects are usually characterized by tight schedules and budgets. The initial cost of employing simulation studies is not favourable to building developers. Building developers may have minimal interest in the long term performance of the building because the completed buildings are usually leased out and are not occupied by the building owners or developers.

Hien et al. (2000) conducted a survey among architectural and engineering consulting firms to investigate the usage of simulation programs in their professional practise and revealed that only 15.6% of the firms used energy and HVAC sizing simulation programs and approximately 70% of the respondents did not use these programs until the design development phase. The author also commented that most of the programs were developed and used for the purpose of design verification and to meet building regulation requirements, and the users did not necessarily use them as a design tool for improving energy performances. Although, it can be argue that the application of these computer programs in enhancing overall building energy performance has increased due to the technological advancements and changing perceptions and demands of high performance buildings over the past decade, the potential of utilizing thermal simulation programs throughout the life-cycles of buildings is still far from being fully realized.

2.4 Concluding remarks

The application of thermal simulation can facilitate better understanding on building design problems with respect to energy and thermal performance. A number of thermal simulation programs are now available and offer wide-ranging level of details. Users should review the programs'' capabilities and limitations, and select the most appropriate simulation tool in accordance to the scope of their project.

Although there are barriers to adopting thermal simulations as standard practises in the industry, the drastic improvements to computing power, changes of perception, and the ever-increasing demand on high performance buildings would likely help to promote the use of these programs in the years to come.

3. Application of thermal simulations during the schematic design phase

3.0 Introduction

It is becoming increasingly apparent that there is a need to construct buildings that are more energy-efficient and have a lower environmental impact. In order to build such high performance buildings, while avoiding or minimizing incremental costs, building design teams employ the Integrated Design Process (IDP). This approach has been recently adopted in the North American context and has become the standard practise for all high performance building designs (Cascadia Green Building Council, 2010; IEA, 2002).

IDP aims to maximize the opportunity for integration and collaboration between building systems early in the design process with major design decisions being made by a broad team of expertise. Professionals with different background share ideas and their expertise at the early stages of the design process, and therefore IDP often results as an iterative process, where designs for the different building systems progresses in parallel. This is in contrary to the conventional design process, which is often described as a sequential design process, from one specialty to another; from architects to engineers and contractors. Generally, in a conventional process, the architect proposes a design which determines the general massing schemes, orientations, building envelope, geometry, and materials to be used. The mechanical and electrical engineers will then be asked to suggest appropriate systems for the as-designed building. There is a limited possibility of optimization during the conventional process and opportunities for combined benefits are missed, while optimization in the later stages of the process is often costly and impractical due to technical and time constraints (IEA, 2002). IDP, on the other hand aims to bring together the key stakeholders and design professionals to work collaboratively and interactively from the early planning stages to synergistically produce a better, more efficient, and more responsible building.

IDP usually requires additional design effort in the schematic design (SD) phase when compared to conventional design processes (Fig. 4). This is so that the architect, engineers, and other members of the team can be involved in suggesting and evaluating strategies with thermal simulation and simulating the energy implications of the strategies under consideration. This would provide simulated data that would influence design decisions at an early stage when it is more likely to have a major impact on the performance of a building, since the degree of the potential impact diminishes rapidly as the project progresses (Lewis, 2004).

Energy performance of buildings is a complex issue that involves the interaction between active and passive systems, building operation, and the environmental factors that the building is subjected to. Passive systems strategically use the building envelope, building orientation, and geometry to capture and control the various environmental loads such as wind, solar, and rain. In essence, passive systems utilize the resources available on site. On the other hand, active systems imports energy from a remote source and deploy mechanical systems such as HVAC and plumbing, and electrical systems such as lighting to help meet the heating, cooling, domestic hot water, and lighting loads that passive systems could not provide otherwise. In designing an energy-efficient building, it is often preferable, if not essential, to optimize passive systems first. A well designed envelope system can effectively control the heat flow across the building and renders the building to require much less energy from active systems to heat and cool the space (BioRegional, 2009; The Passive House Institute, 2009). Strategies include, but are not limited to:

- Taking advantage of the available solar heat gain during heating season to reduce heating demand
- Strategically place different glazing systems in different orientations to maximize benefits throughout heating and cooling seasons

Conventional design process usually does not involve building energy analysis for predicting energy performance (IEA, 2002). As part of an IDP, during the schematic design phase, detailed building energy analysis can be conducted with thermal simulation programs to evaluate the performances of different low-energy envelope strategies. Studies have found that by far the most significant contributor to energy losses, and therefore the most significant opportunity for energy performance improvements, is the building envelope (Brostorrn & Howell, 2008; Hastings, 2004). For example, annual heating energy consumption was reduced by approximately 70% at the Riverdale NetZero (RNZ) Energy House, Edmonton, Alberta with the implementation of an advanced envelope system (Hastings, 2004). Thermal simulation programs provide an effective way in evaluating the performances of different envelope designs virtually, with relatively small time and monetary investments. As part of an IDP, architects can make use of thermal simulation results and make changes to the building design accordingly.

The following section will demonstrate the application of thermal simulation studies to building designs during schematic design phases through a detailed documentation and discussion of a case study.

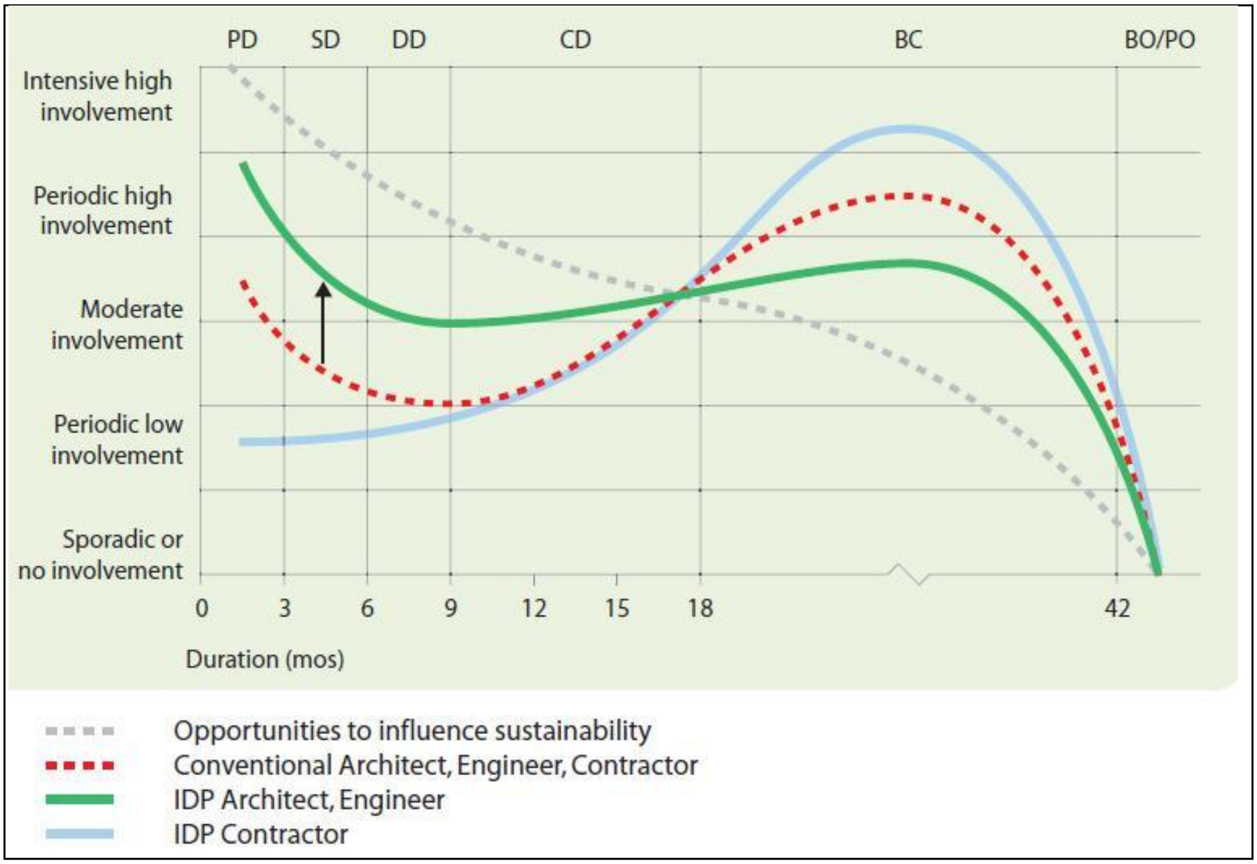

Figure 4 - Design Team involvement; PD (Preliminary Design), SD (Schematic Design), DD (Design Development), CD (Construction Documents), BC (Bidding, Construction, Commissioning), BO (Building Operation), PO (Post occupancy) (Cascadia Green Building Council, 2007)

3.1 Background

In the Toronto downtown east area, as part of a community revitalization project, apartment buildings and town homes that can accommodate 12 500 people are scheduled to be constructed within the next 15 years. The revitalization project was launched in 2006 as a six-phase, 15-year, $1-billion project aiming to transform Canada's largest publicly funded community into a healthier mixed residential community with 5 115 household units.

It is the mandate of the design team to revitalize the area as a "green community" with lower CO_2 emissions and energy savings, and one of the design principles that this project adopted is to achieve high energy efficiency in buildings. All the building designs for this revitalization project will be guided by the requirements of the LEED (Canadian Green Building Council, 2004) green building rating system and many of the buildings are registering to be LEED certified.

Block 12 is a proposed 12-storey, 163-unit multi-unit residential building (MURB) to be located in the revitalized community. The architect and developer intended to achieve higher energy-efficiency by improving the energy performance through the implementation of an advanced envelope system. This study is a vital part of an integrated design process (IDP) aimed to provide simulated data that would influence design decisions at the schematic design phase when it is more likely to have a major impact on the performance of a building. It is the objective of the project team to initiate an ongoing collaborative effort between industry and academia to enhance the performance of not only the subject building but other related projects.

A list of low-energy envelope strategies was proposed and was shortlisted on account of their merit, and technical and financial feasibilities. Discussions were made with engineers and design professionals. The engineers have a clear understanding of the objectives and specific priorities of the architect. They also have abundant experience with the technical viability of the different strategies proposed. Following consultations with professionals, nine design strategies were shortlisted.

This study examined nine design strategies with thermal simulations to reduce the space heating and cooling energy consumption of this MURB and these strategies include:

- Increasing insulation level
- Manipulating thermal mass distribution
- Increasing air-tightness
- Utilizing exterior window shading
- Changing absorptance of external wall
- Installing a thermal break system at balcony connection
- Installing Insulated Concrete Forms
- Installing exterior overhang
- Changing window configurations

The first part of this study will provide an overview of the research area on low-energy envelope designs in MURBs. Key findings in this study area will be highlighted and weaknesses and gaps of current and previous studies will be discussed. The procedures used in constructing the models and the details of the simulation model are then described. Results and discussions are then presented, followed by the concluding remarks of this study and future work.

3.2 Previous research

A combination of theoretical analysis and literature review was undertaken through a series of library research to highlight key findings in this study area and discuss on weaknesses and gaps of current and previous studies In most climatic regions, proper design and combination of insulation and passive components such as direct heat gain from windows, and thermal mass of exterior walls and interior mass, etc., can greatly reduce the heating and cooling energy consumption of buildings (Harvey, 2009; Parker, 2009). Although there have been abundant studies of low-energy consumption houses in North America (Harvey, 2009; Parker, 2009), similar studies have rarely been done for MURBs. Some studies have been conducted on low-energy MURB design in cold climates in other parts of the world, predominantly in Europe (Hastings, 2004), but none of the studies investigated the relative effectiveness of individual building envelope characteristics in reducing heating and cooling energy consumption.

Hastings (2004) compared the energy savings for five low-energy MURBs in central Europe. Three of the five met the Passivhaus standard (The Passive House Institute, 2009), and one of the requirements of the Passivhaus standard is to have space heating demand less than 15 kWh/m^2/annum (54 MJ/m^2/annum) The five MURBs are all highly insulated with U-values for the roofs averaging 0.12 W/m^{2}K, walls 0.14 W/m^{2}K, and windows 0.86 W/m^{2}K. Two of them have large window areas (>50%) to capture light and passive solar heat and large balconies to provide seasonal shading. This study also observed that thermal mass in highly insulated and air-tight buildings is useful for providing better summer comfort, as demonstrated in two of the five MURBs. However, the MURBs studied are only three to four-stories high and therefore findings might not be directly comparable to that of the subjected MURB, which is considerably bigger in scale. As well, this study did not consider the relative performances of individual building envelope characteristics, and the effect of thermal mass during the heating season was not a part of his investigation. The Canadian Mortgage and Housing Corporation (CMHC) (2004) reported a study in 2004. A 15-storey 112-unit MURB was subjected to retrofit and the total energy consumption before and after the retrofit were simulated using eQuest (DOE-2, 2007). The application of Exterior Insulation Finishing System (EIFS) was shown to have decreased gas consumption by 3.2% compared to the basecase. Sealing doors and window perimeters on the other hand, reduced gas consumption by 0.9%. Economic analysis determined that the payback period of cladding upgrade was 147 years, while sealing doors and windows only requires 21.8 years. Unfortunately, the parameters used in the eQuest simulation model, such as occupancy schedule and building envelope configurations were not detailed and therefore the applicability of the results is limited. As well, CMHC's study only focused on the two envelope upgrades mentioned above and neglected to evaluate other low-energy envelope strategies. Smeds & Wall (2007) reported a study in 2007, which investigated the key design features of high performance MURBs for improving energy efficiency in cold climates. Through simulation with DEROB-LTH, the heating load of a 16-unit MURB in Sweden built to the target requirement set by IEA Task 28 (IEA, 2005) was approximately 83% less than that of a referenced building built according to the local building code of 2001. Smeds & Walls' study however only reported the total energy consumption reduction and did not investigate the reduction of individual design features. As well, similar to Hastings's study, the size of the MURB is quite small, with a higher surface area to volume ratio when compared to larger buildings. Harvey (2009) reviewed literature on low-energy building designs. He summarized the energy savings of two post-retrofitted MURBs in Switzerland, and savings up to 88% in heating load were recorded with comprehensive envelope upgrades. However, details of these buildings and retrofits were not divulged.

None of the above studies investigated the effectiveness of individual building envelope characteristics on reducing the heating or cooling energy consumption of buildings. Conversely, there have been some studies focusing on this area in milder climates, mainly in Southeast Asia. Cheung et al. (2005) conducted a simulation study with TRYSYS on a 42-storey MURB in Hong Kong and found that up to 29% reduction in cooling energy consumption can be achieved by increasing insulation of the exterior walls. Cheung et al. also reported that the thermal capacitance of the external wall has different effects on the annual required cooling energy and peak cooling load. The reduction of annual required cooling energy was maximized when thermal capacitance was minimized, while reduction of peak cooling load is maximized when thermal capacitance was maximized. It was also reported that up to 12% reduction in annual cooling energy consumption can be achieved by reducing the exterior wall surface solar absorptance by 30% reduction in exterior wall surface solar absorptance. However, the study was conducted with Hong Kong climate, which has a Heating Degree Day (HDD) of only 77. Although this study provided detailed results on the relationship between the cooling energy consumption and the effect of different low-energy envelope design strategies such as insulation, thermal capacitance, color of external wall, glazing system, window area, and shading, the difference in climatic conditions and building design makes the results difficult to be interpreted in the North American context.

Yu et al. (2008) conducted a dynamic simulation with eQuest on a six-storey MURB in Changsha, China and shows that a reduction of 21% and 35% on heating and cooling energy consumption can be achieved with combining different low-energy envelope features. Yu et al. considered the implications of where to locate insulation in a precast concrete panel wall system and identified that heating energy consumption is the least with interior insulation, followed by exterior and middle insulation in precast concrete panels. The study also confirmed that the addition of insulation conforms to the rule of “diminishing return” as the saving for both heating and cooling energy consumption declines for every additional insulation increment. Yu et al.‘s study also determined that the differences of solar radiation absorptance with different building exterior surface materials affect the heating and cooling energy consumption quite considerably. Also, the relationship between heating and cooling energy consumption to the window-to-wall ratio follows a strong linear relationship. On the other hand, the effects of varied window-to-wall ratio and presence of shading elements are negligible to the overall heating and cooling energy consumption while different surface absorptance level poses a larger impact on reducing energy consumption. Yu et al. also reported that horizontal shadings of 1.5m overhangs can decrease 4.1% of the cooling energy consumption but increase 1.9% of the heating energy consumption. Vertical shadings with 1.5m fins are similar to that of its horizontal counterpart but it only increases heating consumption by less than 1%. However, there are limitations to this study. Firstly, the study is conducted in a mild climate (HDD 1556) when compared to that in Toronto (HDD 3570). Secondly, the heating and cooling setpoint temperature is 18^{o}C and 26^{o}C, which is not representative with the typical setpoint temperatures in Canada. Thirdly there exist some drawbacks in conducting simulations with eQuest when compared to EnergyPlus. eQuest is based on DOE-2 while EnergyPlus is based on the most popular features of both DOE-2 and BLAST. Crawley et al. (2005) compared the features of multiple simulation programs and reported that eQuest lacks certain numerical iterative features such as non-linear system solutions and the time step approach does not dynamically varies based on solution transients. eQuest also does not feature solar gain calculations with external building components for inter-reflections, solar gain through blinds for different transmittance for sky and ground diffuse solar, user specified shading control, and hybrid natural and mechanical ventilation, etc. The lack of these features might have had an impact on the simulation results.

In general, the literature review shows that previous studies on low-energy buildings in cold climatic regions have focused on houses. For the ones that were conducted on MURBs, they usually focused on the collective benefit of the entire building envelope and lacked sensitivity analyses on individual envelope characteristics on reducing energy consumptions. There is a lack of comparative study on the effectiveness of individual building envelope characteristics on reducing the heating or cooling energy consumption of buildings.

3.3 The Basecase model

This study aims to investigate the performances of the aforementioned building envelope design strategies with the thermal simulation software, EnergyPlus.

A Basecase model was established with DesignBuilder and EnergyPlus in accordance with Block 12's preliminary design drawings and mechanical and electrical specifications. This building project was under schematic design at the time the study was conducted. A copy of the EnergyPlus simulation files is as included in the CD-Rom provided alongside with Appendix B of this thesis. The building (Fig. 5) is a 12-storey, 163-unit MURB to be located in Toronto, Ontario. The building consists of twelve levels with an amenity penthouse. The total floor area is approximately 12,932 m^2 (139,195 ft^2). DesignBuilder v. 2.0.4.002 was employed to generate the geometric details of this MURB (Fig. 5-6). The as-designed Basecase DesignBuilder model was established in accordance with the detailed drawings provided by the architects. The DesignBuilder model was then exported to EnergyPlus in specifying operational parameters such as Heating, Ventilating, and Air Conditioning (HVAC) equipments and systems, schedules, sizing, and internal load, etc. Simulations were then performed directly from EnergyPlus v.3.1.0.027.

As discussed in Section2.3 of this thesis, one of the major challenges faced by design teams in conducting thermal simulation studies in the schematic design phase is the unavailability of certain parameters for model input. At an early design stage, information pertaining to the building design was significantly restricted, and therefore assumptions need to be made in the thermal simulation model. Progress reports were regularly prepared and submitted to the engineers responsible for the various building systems to cross-check envelope, mechanical, and electrical details employed in the model. Design changes to the different systems were constantly being made. In order to maximize the precision of the thermal simulation model, it is vital to incorporate these design changes into the simulation model. Communicating frequently with the design team to be aware of any design changes is therefore necessary. Although this process was resource-intensive, the adoption of the IDP offered a conducive and integrative environment in gathering all necessary information without major effort and delays. All members in the design team were aware of the importance and potential benefits of the thermal simulation study and therefore provided supportive effort throughout the process.

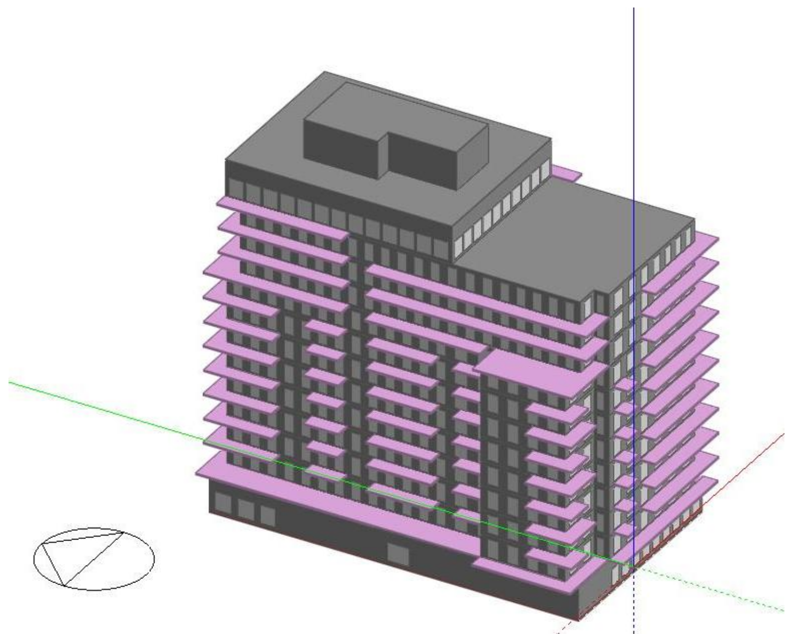

Figure 5 - Geometric representation of the building

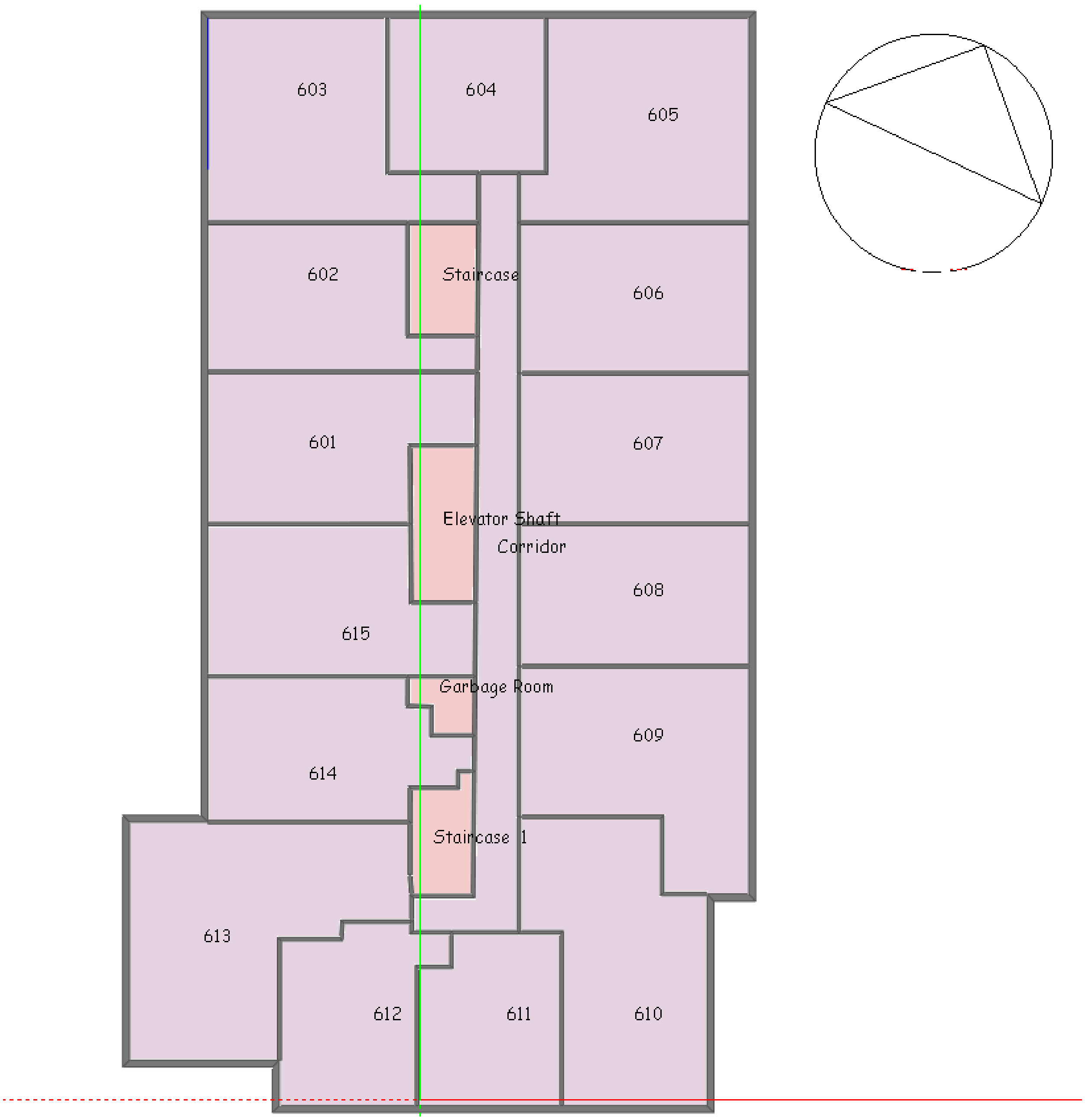

Figure 6 - Simplified floor plan for a typical floor of the building

3.3.1 Basecase model parameters

Referring to the preliminary design drawings provided by the architect, the external walls are composed of precast insulated concrete panel, which consists of a sandwich of two concrete layers at 125mm and 105mm thick, a layer of 75mm semi-rigid insulation foam in between, and a layer of gypsum wallboard on the interior surface. The indoor partition walls are each composed of three layers, a sandwich of two gypsum wallboard with a 100mm concrete layer in between. The floor slab is composed of 200mm concrete slab with a layer of gypsum wallboard underneath. The flat roof consists of four layers with stone ballast roofing as the outermost layer, followed by 104mm of Extruded Polystyrene (EPS) insulation, 280mm concrete slab, and layer of gypsum wallboard. The properties of the various materials used in the model are summarized in Table 2. The thermal resistance value of the envelope components are as listed in Table 3.

Table 2 - Thermal properties of materials

	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)
Precast concrete	2400	1000	1.74
Gypsum wallboard	1000	1000	0.4
Semi-rigid insulation	20	840	0.036
Expanded Polystrene insulation	25	1400	0.035
Stone Ballast	1840	840	0.36

Table 3 - Thermal resistance of base case building envelope

	U (W/m^{2}K)	Thermal Resistance RSI (m^{2}K/W)	R (Imperial)
Exterior Wall	0.414	2.42	13.7
Slab-On-Grade Floor	2.035	0.49	2.8
Interior Floor	2.221	0.45	2.6
Flat Roof	0.285	3.51	19.9
Windows (operable and fixed)	2.27	0.44	2.5

The windows are Argon gas filled, double glazed units, consisting of outer pane of 6 mm thick clear Ti-R glass with low-E coating on the second surface, and inner pane of 4 mm thick glass. Windows are framed with aluminum. In accordance to the architect's specifications, all windows have a solar heat gain coefficient of 0.44 and a U-value of 2.27 W/m^{2}K. Light transmission is set as 0.669 for all fixed and operable windows. The window-to-wall ratio is 40%.

The power intensity of the lighting system is assumed to be 10 W/m^2 for the residential units, 8 W/m^2 for the corridors, 6.5 W/m^2 for floor 13's amenity space, 7 W/m^2 for garbage areas, and 8.6 W/m^2 for ground floor's lobby area. With the exception of MURB units, all lighting power densities (LPD) employed are in accordance to details provided by the BET from Trow. The LPD for the residential units is in accordance to Yu et al.'s (2008) study.

The residential units are assumed to have a plug demand of 3 W/m^2 during occupancy, while public spaces have a plug demand of 8 W/m^2. An occupancy density of 0.035 people/m^2 is assumed. The residential units are occupied in accordance with the occupancy schedule as illustrated in Table 4. The mean floor areas are 37m^2 for studio units, 59.6 m^2 for one-bedroom units, and 81.4 m^2 for two- bedroom units. The infiltration rate is 0.25L/s per m^2 of gross above grade envelope area, which is in accordance with the Procedures for Modeling Buildings to Model National Energy Code for Buildings (MNECB) and Commercial Building Incentive Program (CBIP) (NRCan, 2002). With the envelope area and volume at 7,124m^2 and 38,800m^3, an air change rate of 0.17 ACH at normal operating condition was employed in the model. This air infiltration rate lies within the range reported in previous studies by different research groups. Feustel & Diamond (1998) from Lawrence Berkeley National Laboratory (LBNL) reported an air infiltration of 0.2 ACH for a 150-unit MURB in Chelsea, Massachusetts; Emmerich et al. (2005) reported an average of 0.232 ACH for four-storey MURB across the USA. Section 5.5.7 of the "Procedures for Modeling Buildings to MNECB and CBIP" specifies the minimum fresh air to be 44.5 L/s for one-bedroom and studio residential units and 64.5L/s two-bathroom residential unit with a kitchen exhaust and clothes dryer. All fresh air is assumed to be delivered by mechanical equipments and that no natural ventilation is available to the unit.

The HVAC system for the Basecase model is two-pipe fan coil units with heat recovery ventilators at 68% effectiveness in each residential unit. The heating set-point and setback temperature are set as 22 ^{o}C and 20^{o}C respectively, Cooling set-point and setback temperatures are set as 24 ^{o}C and 26 ^{o}C. In accordance to the designer's specifications, corridors are served by an air handling unit providing ventilation of 0.3L/s•m^2 (0.06 cfm/ft^2). Large common areas on ground and 13th floor are conditioned with two-pipe air handling units with economizer function for the shoulder seasons. The actual building is connected to a district energy system, but for the purpose of this study, a central plant is assumed to supply space heating and cooling. A central modulating boiler with an efficiency of 0.8 and chillier with COP 3.8 provides hot water heating and cold water chilling for the hot and cold water loops, which provides heating and cooling for all the air handling units for the corridors, public spaces, and residential units.

Table 4 - Occupancy Schedule

	MURB units	Common Areas
Monday to Friday	7pm-8am	24 hours
Weekends	9pm-11am	24 hours
Holidays	9pm-11am	24 hours

3.4 Results and discussion

On the basis of the building characteristics described above, the heating and cooling energy consumptions were predicted by using EnergyPlus based on the Canadian Weather for Energy Calculations (CWEC) data file from the nearest available weather station (Toronto International Airport). The impact of the nine low-energy wall envelope characteristics on heating and cooling energy consumption are investigated and presented in this section.

3.4.1 Insulation level

Different levels of thermal resistance can be achieved by adding EPS thermal insulation to the exterior walls of the models. The thermal resistance of the external wall was modified by increments of 25mm EPS insulations within the concrete panels. Fig. 7 illustrates the simulation results. As expected, heating energy consumption decreases as thermal resistance increases; insulation reduces the heat transfer rate and thereby reduces the energy requirement for space heating. However, increasing the insulation thickness gives diminishing returns on the energy saved. This corresponds to studies conducted previously (Hasan, 1999; Dombayci et al., 2006), for which were taken place at milder or even subtropical climates.

On the other hand, cooling energy consumption remains fairly constant as insulation thickness increases. Monthly simulation results reveal that the building with increased insulation requires space cooling earlier in the year as oppose to Basecase. The heat generated by internal sources and gathered from the sun may not be transmitted to the exterior as readily as Basecase because of the increased insulation. This is in contrary to previous studies (Cheung et al., 2005; Yu et al., 2008), where reductions in cooling energy consumption was recorded with incremental increase in insulation thickness in MURBs in Hong Kong and Changsha, China. However, this finding is aligned to the studies by Masoso & Grobler (2008) and Kim & Moon (2009). Using eQuest, Kim & Moon (2009) conducted a simulation study on a low-rise residential house in Detroit, Michigan and found that insulation is primarily beneficial for reducing heating energy in winter, but has no practical benefit for saving cooling energy consumption in summer. Masoso & Grobler (2008) found that cooling load might actually be increased when extra insulation is added on the wall envelope and would depend on the orientation, occupancy patterns, and glazing system, etc. of the building. However, it is important to note that natural ventilation was not taken into account in the simulation model.

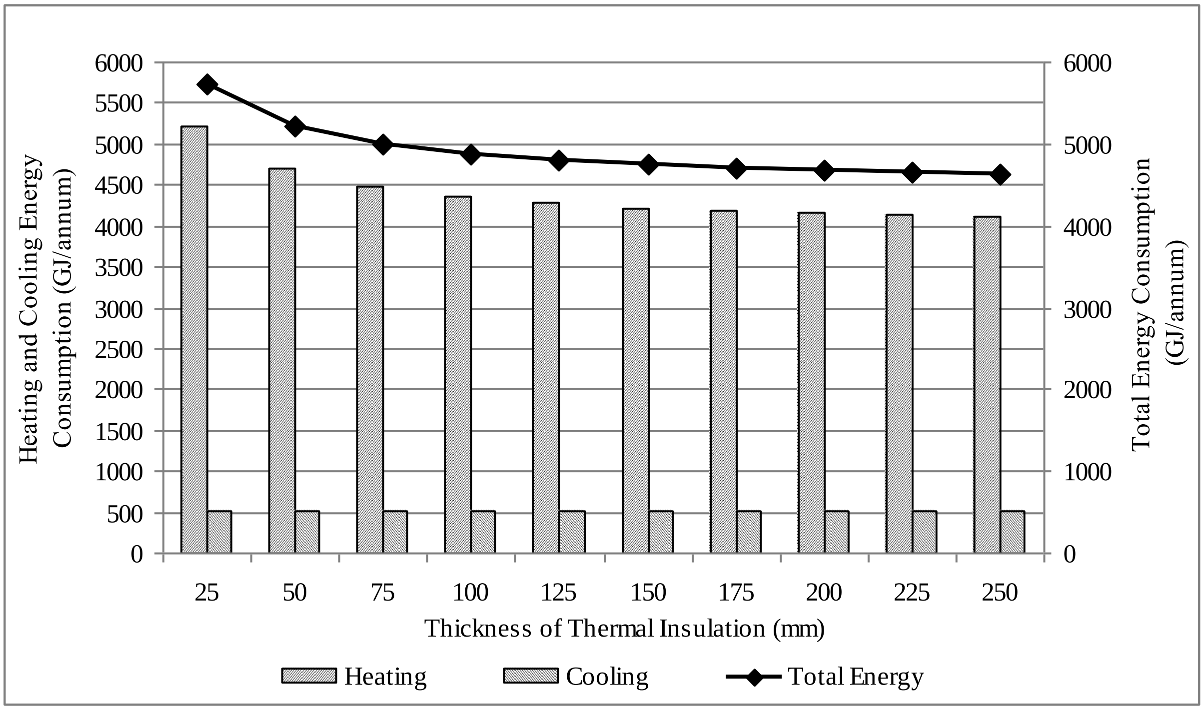

Figure 7 - Effects of insulation thickness on building's heating and cooling energy consumption

3.4.2 Thermal mass

Simulation results also show that changing the thermal mass of the external wall has trivial effects on the heating and cooling energy consumption (Fig. 8-9). The exterior wall configuration was manipulated to investigate the impact of thermal mass on the space conditioning energy consumption of the building. The EPS insulation layer is moved from the middle of the external wall to the inner and outer surface and the thickness is increased by increments of 50mm. The simulation results do not indicate any significant saving due to thermal mass by manipulating the location of the EPS insulation layer. Increasing the thermal capacitance of the external wall by moving the 75mm insulation layer from the middle surface to the outer surface would lead to a reduction of heating and cooling energy consumption marginally. The heating and cooling energy consumption differences observed by varying the configuration of the external wall are too small to be significant to conclude any potential saving.

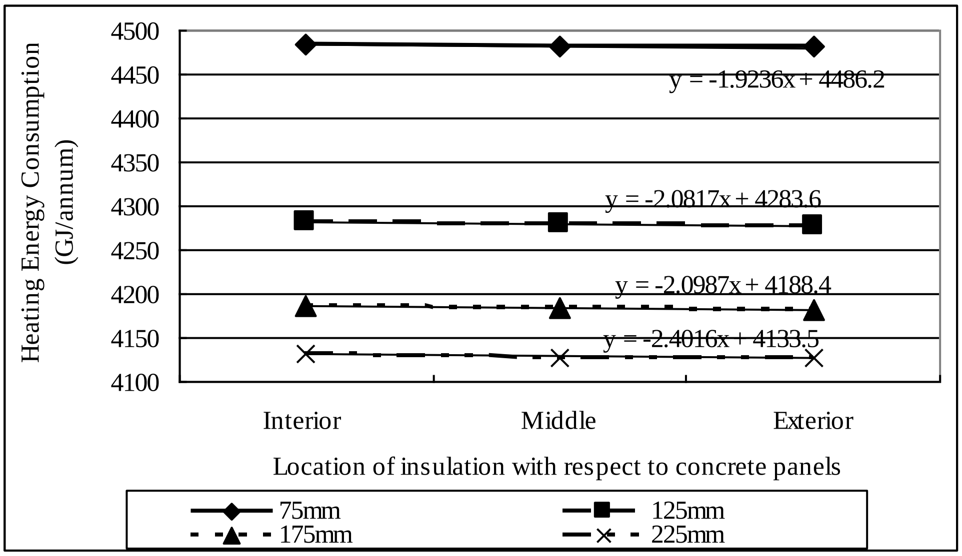

Figure 8 - Effects of wall configurations on building's cooling energy consumption

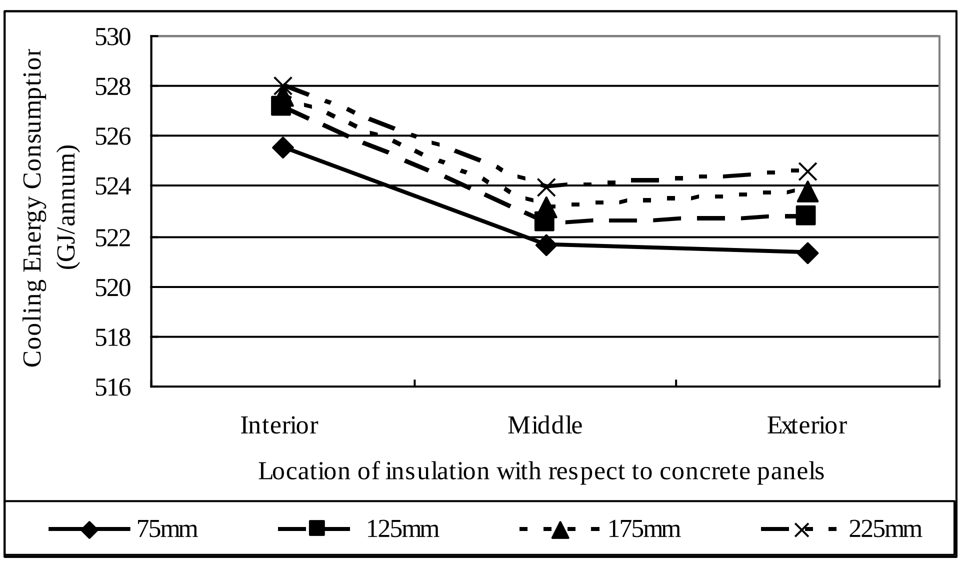

Figure 9 - Effects of wall configurations on building's heating energy consumption

3.4.3 Air-tightness

A literature review was conducted on previous studies on air-tightness in MURBs in North America and reveals that while air infiltration represents a major contribution to heating demand (CMHC, 2001), the complexity of the structural, mechanical, and thermal systems of MURBs makes it difficult to fully understand and predict the air-tightness levels in this type of building (Persily, 1999; Proskiw & Philips, 2008; Genge, 2009). Current building certification programs such as LEED also do not recognize the impact of improving air-tightness in reducing the heating and cooling energy consumption of buildings.

Sherman & Chan (2004) reviewed over 100 publications relating to air-tightness around the world and found that while more than 100 000 low-rise residential houses have been tested and documented since blower or fan door testing was introduced in the 1970s, only less than 500 units in MURBs have been tested for air-tightness worldwide. The sample set for MURBs is practically insignificant in comparison to the vast number of low-rise residential houses tested and documented. The largest database of low-rise residential houses is maintained by the Energy Performance of Buildings Group at Lawrence Berkeley National Laboratory (LBNL) which has over 73 000 testing data from the USA. No such database exists for MURBs. Typical values for the different category of air-tightness level in low-rise houses can be found in the ASHRAE Handbook of Fundamentals (2005) and is as summarized in Table 5 in normalized leakage rate (NLR) (cfm/ft^2 and L/s•m^2 at 75 Pa). No such baseline values are provided for MURBs.

Table 5 - Air-tightness values as per ASHRAE handbooks - fundamental

	NLR_{75} (cfm/ft^2 $_{envelope\ area}$)	NLR_{75} (L/s•m^2 $_{envelope\ area}$)
Leaky	0.6	3.05
Average	0.3	1.52
Tight	0.1	0.51

CMHC (1990) evaluated the air leakage rates through the building envelope in ten buildings across Canada. The results indicated the NLR ranges from 2.10 to 3.15 L/s•m^2 at 50 Pa (0.54 - 0.90 cfm/ft^2 at75 Pa) during suite fan depressurization testing. In a more recent Canadian study (Finch, 2007), four buildings in Vancouver, BC were air leakage tested. Two of which are four-storey wood-frame MURBs with one of them built in the early 1990’s and the other one built in 2002. The other two are six- and 26-storey high concrete framed MURBs built in the early 1990’s and late 1980's respectively. The investigation showed that the two wood-framed buildings have much higher air leakage rates than the two concrete-framed buildings. The results indicated that NLR were found to be in the range of 0.56 -1.28 L/s•m^2 at 50Pa (0.14-0.33 cfm/ft^2 at 75Pa) for the two concrete frame buildings and 1.74 - 3.59 L/s•m^2 at 50Pa (0.45-0.92 cfm/ft^2 at 75Pa) for the two wood framed MURBs.

Table 6 lists the reported air-tightness level of MURBs in North America by different research groups. Data has been converted to normalized leakage rate (cfm/ft^2 and L/s•m^2 at 75 Pa) using the conversion formulas from Chapter 27 of the 2005 ASHRAE Handbook – Fundamentals.

Table 6 - Reported air-tightness levels from previous studies

	NLR_{75} (cfm/ft^2 $_{\text{envelope area}}$)	NLR_{75} (L/s•m^2 $_{\text{envelope area}}$)
CMHC (1993)	0.23	1.17
Persily (1999)	1.5	7.62
Sheltair Scientific (1999)	0.49	2.49

There is little consistency between the tests, and each building will likely be unique depending on workmanship, construction practices, details, and materials used. Nonetheless, these previous tests provide some guidance on the range of air leakage values to be used in simulations. The model was simulated with different air-tightness levels by changing the air change per hour (ACH) value of the envelope system. ACH 0.1 (0.11 cfm/ft^2 or 0. 56 L/s•m^2 at 75Pa) to ACH 0.4 (0.44 cfm/ft^2 or 2.24 L/s•m^2 at 75Pa) with ACH 0.1 increments.

As illustrated in Fig. 10, infiltration causes heat loss throughout the entire year for all four scenarios. The amount of heat flow differs significantly throughout the year. In January, the difference in amount of heat loss through the envelope is approximately 3.4 times, or 118.78 GJ from ACH 0.4 to ACH 0.1; in July, the difference drops to 3.2 times, or 8.76 GJ. The amount of heat loss via infiltration is comparable to the conductive heat loss via exterior wall. Conduction heat loss through building envelope is recorded to be 104.62 GJ and 44.34 GJ in January and July respectively in Basecase. As seen, infiltration therefore contributes to a major contribution to the heating energy consumption of the building.

Because infiltration plays a much more significant role in winter than in summer, the impact on heating energy consumption is more pronounced than cooling energy consumption with the different ACH levels. As illustrated in Fig. 11, heating energy consumption is reduced significantly from 6074.3 GJ/annum to 3917.5

GJ/annum, or 35.5% as the air-tightness of the building improves from ACH 0.4 to ACH 0.1. In the meantime, by improving the air-tightness of the building, cooling energy consumption decreases marginally from 537.7 GJ/annum to 527.3 GJ/annum, or 1.94%. As shown in Fig. 12, peak cooling demand on the other hand is reduced from 145.1 kW to 130.2 kW, or 10.2%. This illustrates that the peak cooling load can be reduced quite considerably by improving the air-tightness of the building, which could potentially lead to a reduction in sizing of the mechanical equipments.

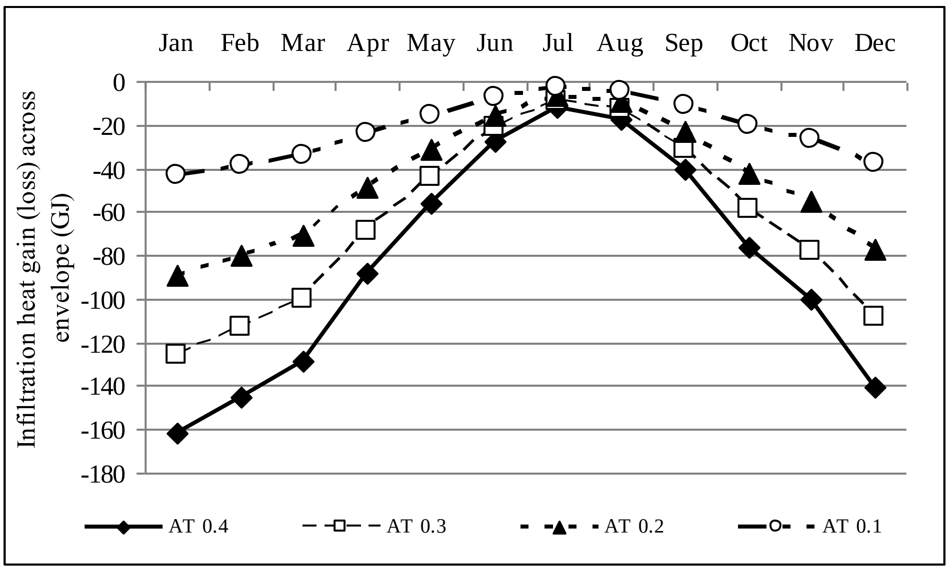

Figure 10 - Building's infiltration heat gain (loss) across envelope system with varying air-tightness levels

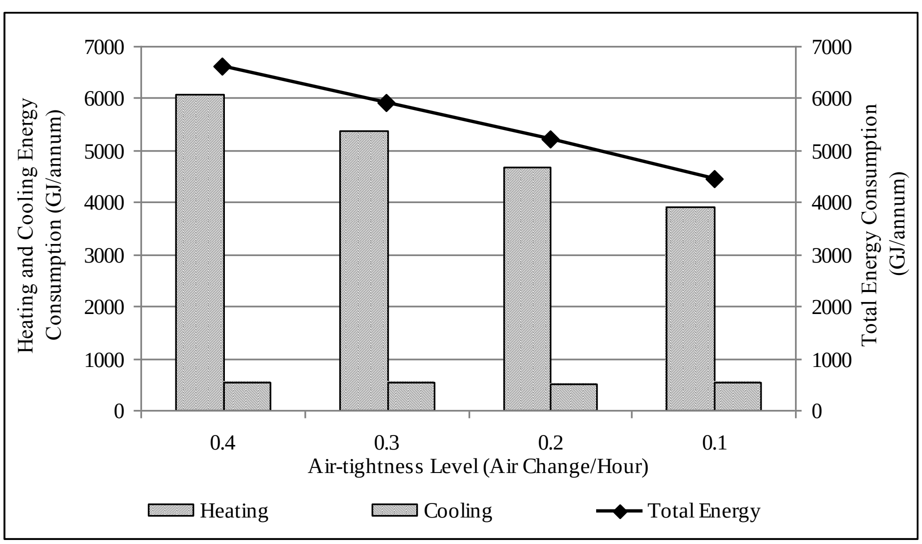

Figure 11- Effects of air-tightness level on Building's heating and cooling energy consumption

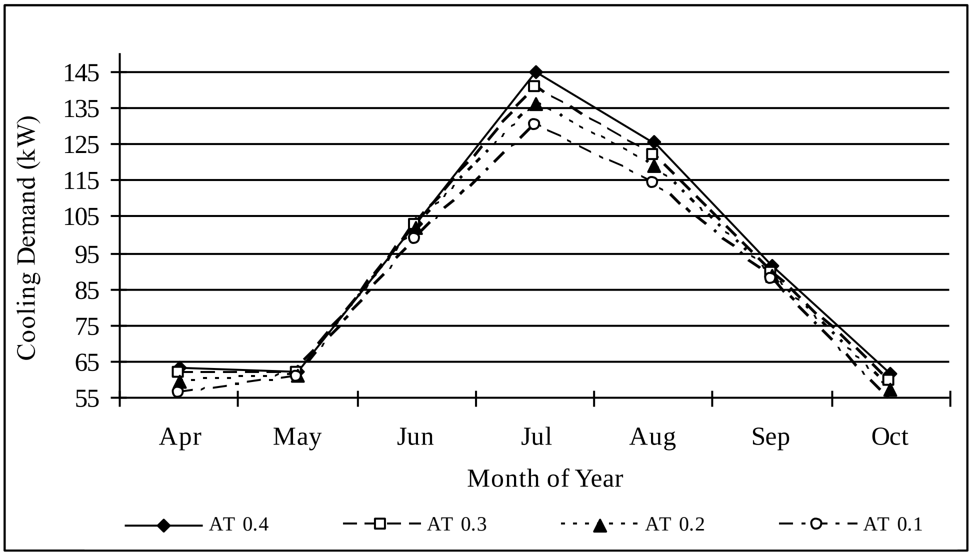

Figure 12 - Effects of air-tightness level on Building's cooling demand

3.4.4 Exterior window shades

The research area on integrating advanced glazing and innovative day-lighting/shading systems in lowering both the lighting and space conditioning load is quite extensive (Kuhn, et al., 2000; Tzempelikos, 2007), but it is not the objective of this study to evaluate the interaction of day-lighting effects with shading system. This part of the study focuses purely on the benefits of installing exterior window shades in reducing heating and cooling energy consumption.

Previous field studies concerning improving thermal comfort and energy performance with using interior and exterior shades were performed at the twin houses of the Canadian Center for Housing Technology (CCHT) (Laouadi et al., 2008). Results showed an average reduction of 4 ± 2% in heating energy consumption by using external rollshutters versus interior venetian blinds. The external rollshutters used however, were either completely closed or opened throughout the testing period. Retractable exterior vertical window shades with high reflectivity slats on both sides were installed on all exterior windows on all four sides of the building. These rotatable and retractable shading devices provide shades during overheated periods and allow solar energy to pass through during underheated periods. The shade-to-glass distance was set to 0.015m, the slat width, separation, and thickness were set to be 0.007, 0.019, and 0.001m respectively. Thermal conductivity of the slats was 0.9. Solar transmittance and reflectance were 0 and 0.8 respectively, and emissivity was set to 0.9.

Two control strategies were evaluated. The first strategy is that the operation of the shading system is controlled by a defined schedule. This is to mimic the case where shades are manually controlled by the occupants in a routine basis. Shades are turned on during summer days to avoid unwanted solar gain and during winter nights to minimize heat loss from the glazing system by means of radiant exchange to the exterior. However, relying on the voluntary actions of occupants to use the shading systems in the way they are planned to be used might be problematic (Kim & Park, 2009); Kim & Park (2009) found that manual control of shading systems at offices might increase the overall energy consumption if the shading systems are not operated properly. Scott et al. (2001) found that the participation rate of adjusting shades during hot summer days to prevent overheating is quite low when compared to other energy conservation actions such as turning off unused lights and adjusting thermostat set-points when house is not occupied. Therefore, as an alternative, the second strategy is that shading systems are automatically controlled with motorized shades. With this strategy, shades are turned on during the day when solar radiation incident on the window exceeds 120 W/m^2, at night-time throughout the year, and if there exists a positive zone cooling rate in the zone. When the shadings are on, they fully cover all of the windows except the frame; when they are off, they are retracted and do not cover the windows. For the two control strategies, four slat angles were evaluated, 0^o, 30^o, 45^o, and 60^o to the glazing outward normal. The slats are parallel to the glazing and faces outdoor when the slat angle is set as 0^o. With the slat angle set as 0^o, the shade is fully extended and the slats are completely closed whenever the shading is on. This slat angle maximizes the overheating protection when it's on, but ignores the need for visual contact to the exterior.

As seen in Fig. 13 and 14, the shades are able to reduce the heat loss through windows by an average of 18.9% and 26.2% for the manual and automated control strategy respectively while heat gain through windows is reduced by 4.4% to 8.3% for the manual control strategy and 4.1% to 9.5% for the automated control strategy. Heat loss via long-wave radiation exchange to the exterior is reduced considerably due to the provision of the shades, especially during cold winter nights. The amount of heat gain decreases as slat angle increases from 0^o to 30^o in both cases. However, as slat angle further increases from 30^o to 60^o, the amount of heat gain increases (Fig. 13-14) and monthly results reveal that the occurrence of increase in heat gain is during summer cooling months. During winter heating months, systems with lower slat angles allows more solar heat in passing through than systems with higher slat angles. Therefore systems with lower slat angles are more effective in blocking unwanted solar heat gain during the summer and allowing more solar heat into the space during winter. The heat flow across the windows was then calculated by subtracting annual window heat loss to annual heat gain and the result is as shown in Fig. 13-14. As seen, for both control strategies in general, the net heat flow becomes more positive, which results in net heat gain as we increase the slat angle. The automated strategy has a higher amount of net heat flow than the manual control strategy. Net heat losses were recorded for all angles controlled by the manual control strategy, while net heat gains were recorded for the automated control strategy. Both heating and cooling energy consumptions are reduced with installing window shades in different slat angles (Fig. 15-16) which leads to a drop of total energy consumption of 6.5% to 6.6% for the manual control strategy and7.9 % to 8.2% for the automated control strategy.

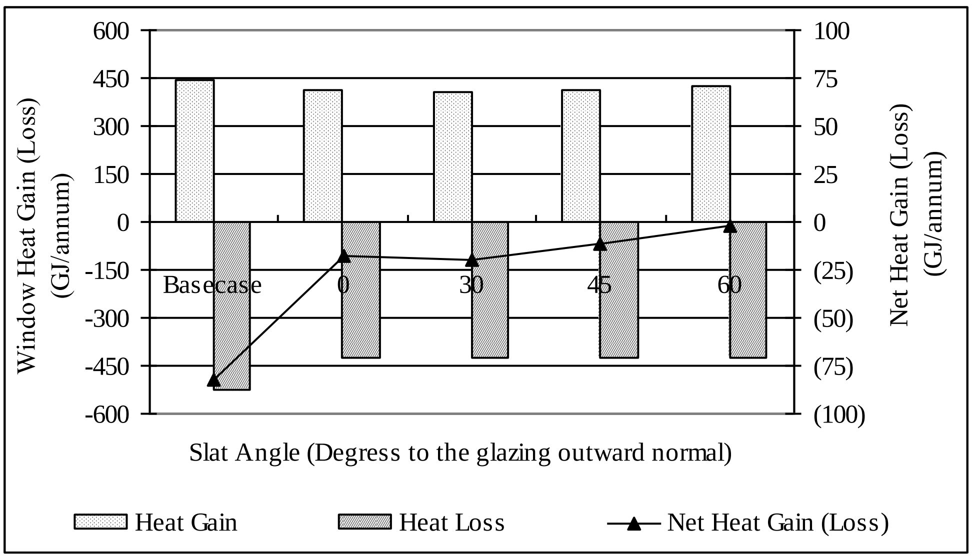

Figure 13 - Building’s window heat balance using shades with scheduled control

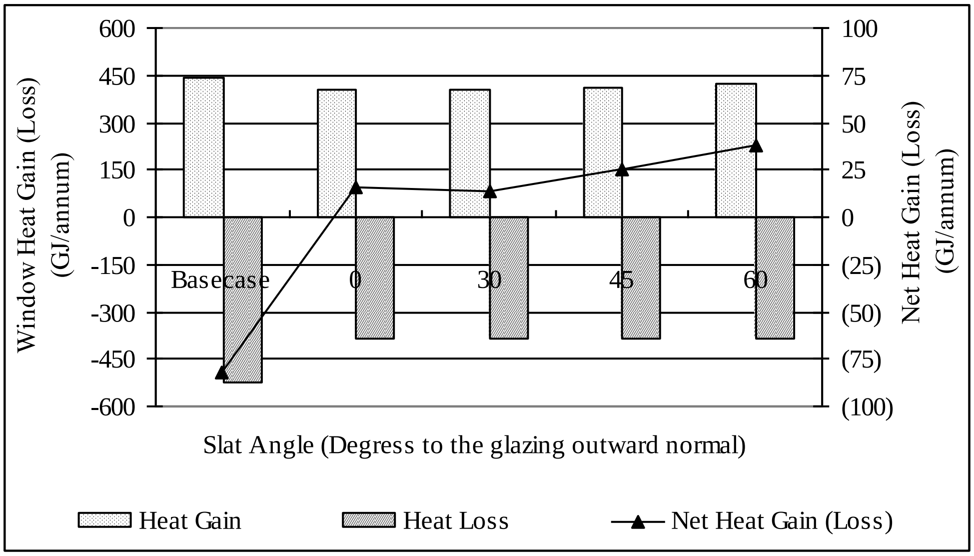

Figure 14 - Building's window heat balance using shades with automatic control

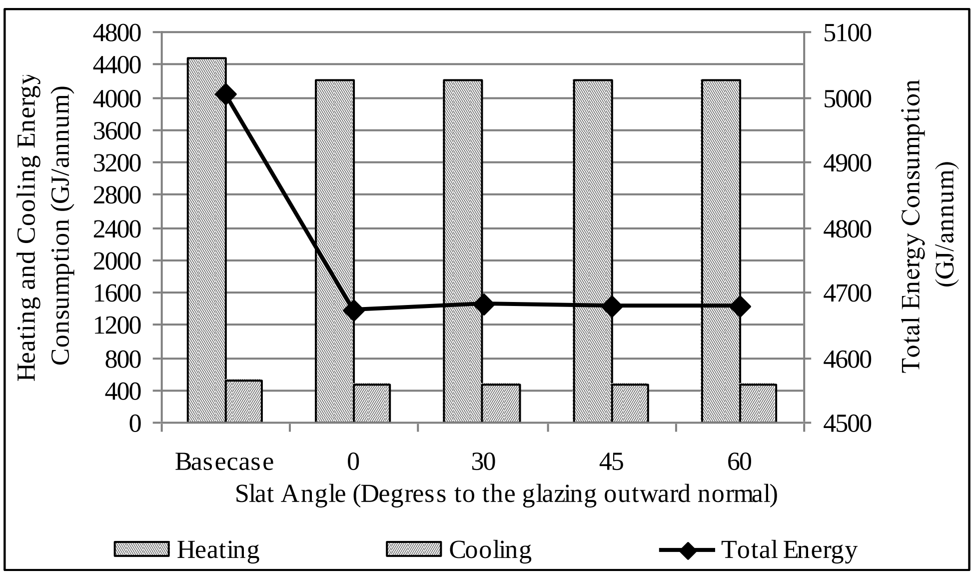

Figure 15 - The effect of window shades with scheduled control on Building's space conditioning energy consumption

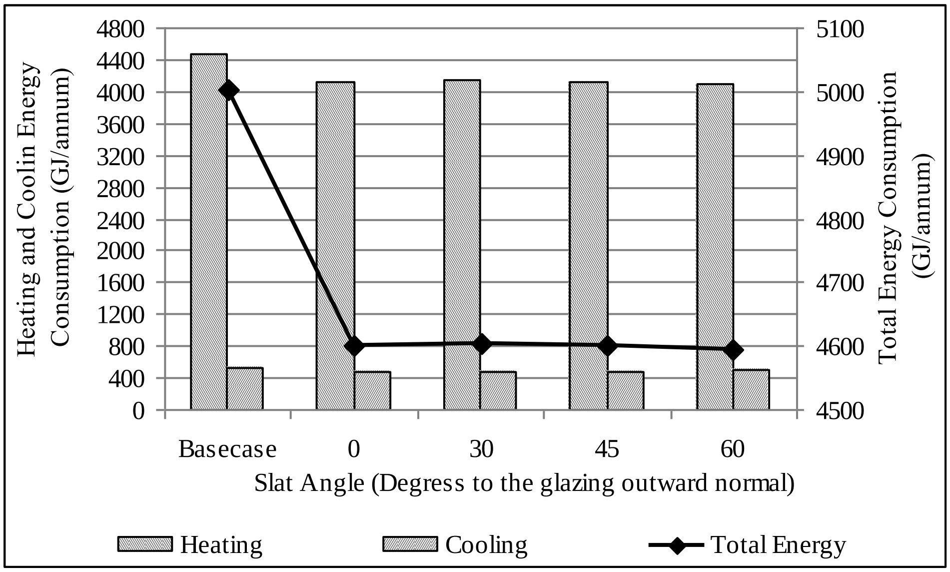

Figure 16 - The effect of window shades with automatic control on Building's space conditioning energy consumption

3.4.5 Absorptance of external wall

Solar absorptance of a wall surface depends on its color and surface texture and poses an effect on the surface temperature. Emissivity is a measure of the ability of a material to emit thermal radiation. Four solar absorptance of the precast wall were evaluated, solar absoprtivity at 0.25 (white), 0.45 (light colors), 0.75 (dark colors), and 0.875 (black).The model was simulated with different wall surface color by changing the absorptance of the exterior precast concrete wall. The results (Fig.17-19) varied with wall surface color. Solar absorptivity and heat loss through external wall displays a perfect positive linear relationship. As the absorptance increases (darker surface color), the amount of heat loss through the external wall decreases. Darker surfaces can more readily absorb the solar heat during the day and contribute to the interior heat balance. As illustrated in Fig. 17, the reduction in heat loss through exterior wall reduces the heating energy consumption by a mere 1.8%, or 80 GJ/annum when absorptance is increased from 0.25 to 0.875; as expected, cooling energy consumption on the other hand is increased by 6.2 %, or 32 GJ/annum (Fig. 18), leading to a decrease of merely 0.9 % for the total energy consumption (Fig. 19). The increase in cooling energy consumption with increasing absortpance is due to the increase in heat gain through the external walls throughout the year. During the summer, the dark surfaces effectively absorb the solar heat and contribute to the space's heat gain, whereas a lighter surface would not absorb as much solar heat and therefore lessen the amount of heat being transferred to the interior. The performance of increasing solar absorptivity on external walls is not as effective as expected and is believed to be due to the climate in Toronto, which is marked by cold winters and relatively warm summers. Simulation results also show that the impact of altering the solar absortpance of the external wall varies with orientation (Fig. 20-21). Heating and cooling load intensity for four residential units facing different orientations from floor 11 are reported. Heating load intensity decreases in all four orientations as solar absorptivity increases from 0.25 to 0.875. As illustrated in Fig. 20, the south-facing wall displays the steepest negative slope as depicted by the equation of the fitted regression line, followed by north-, west-, and east-facing walls. On the other hand, cooling load intensity in all four orientations increases as solar absorptivity increases (Fig. 21); the south-facing wall displays the steepest negative slope, followed by east-, west-, and north-facing walls. More pronounced impact on both heating and cooling load intensity is noted on south-facing

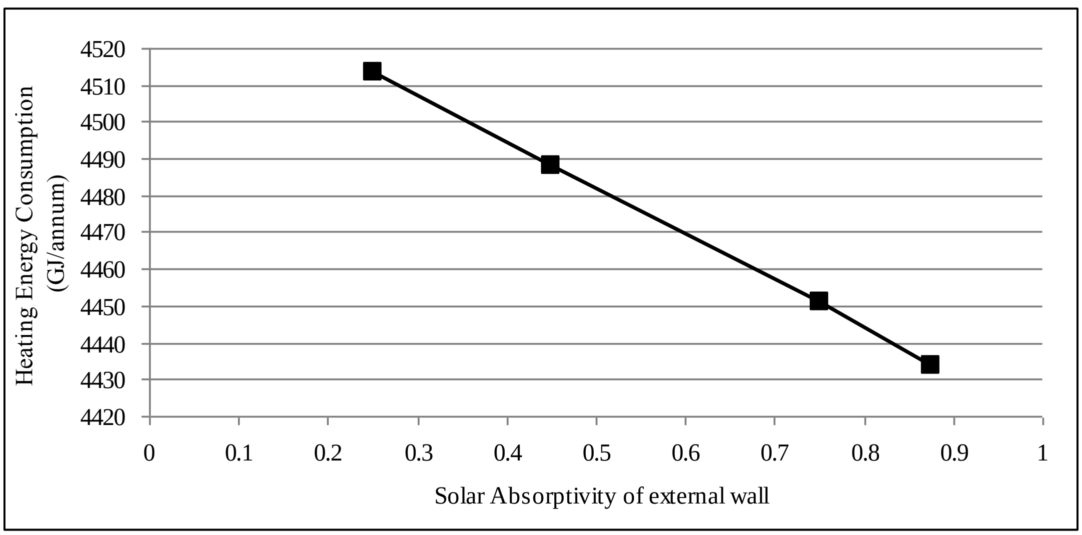

Figure 17 – Effects of solar absorptivity on Building's heating energy consumption

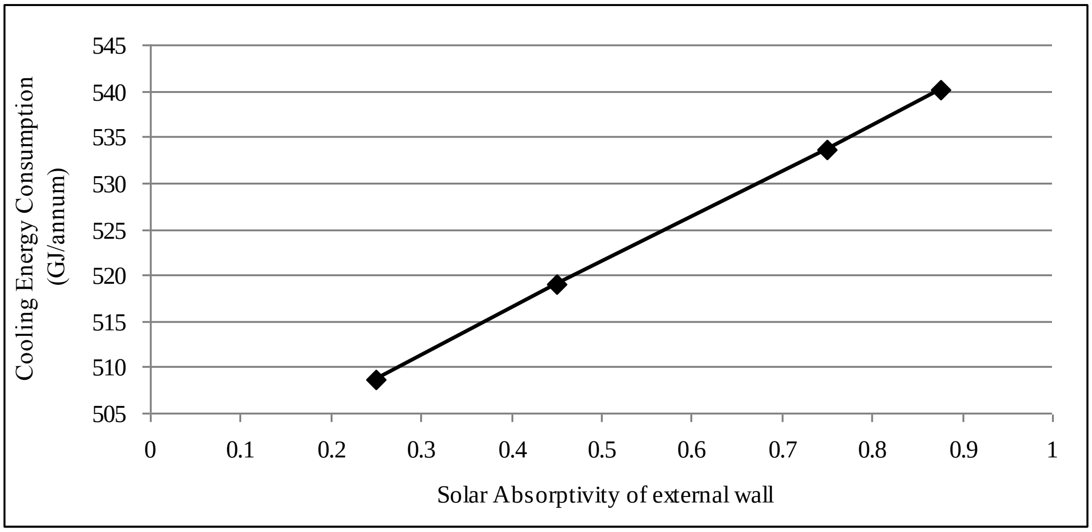

Figure 18 - Effects of solar absorptivity on Building's cooling energy consumption

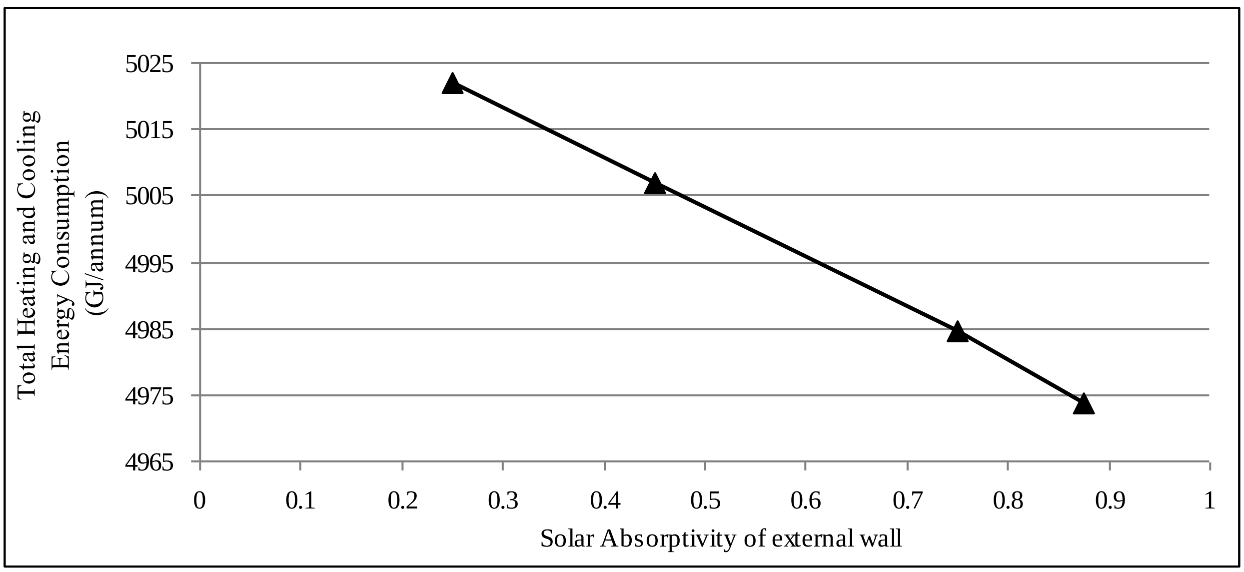

Figure 19 - Effects of solar absorptivity on Building's total heating and cooling energy consumption

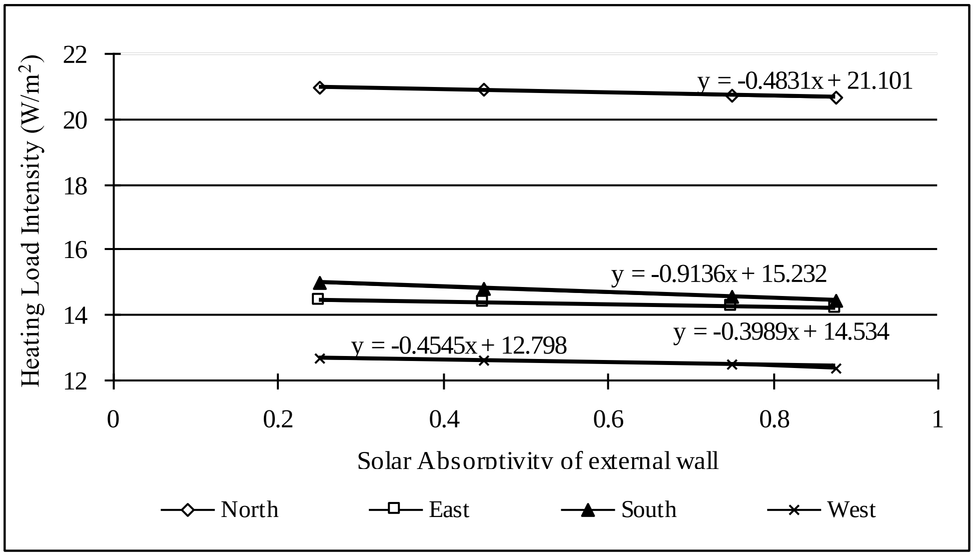

Figure 20 - Effect of solar absorptivity on heating load intensity in individual units facing different orientations

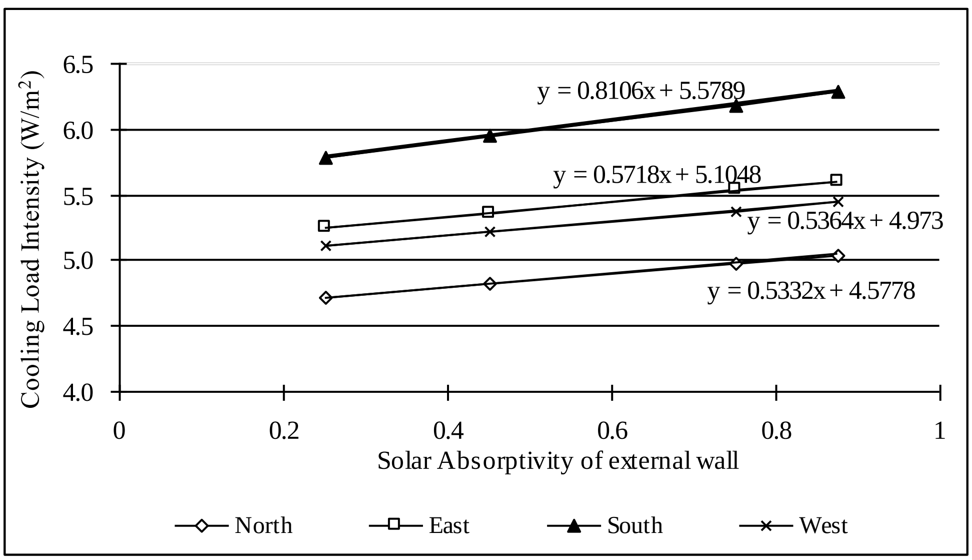

Figure 21 - Effect of solar absorptivity on cooling load intensity in individual units facing different orientations

3.4.6 Thermal break system

A thermal break system used in mitigating the thermal bridge at the concrete to concrete connection of the free cantilever balconies was incorporated into the envelope design to reduce heating and cooling energy consumption of the building. The concrete to concrete connection of the free cantilever balconies creates a continuous path for heat conduction from interior to exterior. The total span of the balconies was approximated to be 932.15m for the entire building. The thermal break system in thermally separating the concrete to concrete connection of the free cantilever balconies to the interior slab was evaluated. The R value at the slab edge (between the slab on the inside and the balcony) was set to be R 13 (80mm of .035 W/(m*K)).

Fig. 22 illustrates the simulation results. As seen, the thermal break system is able to reduce the heating energy consumption of the building by 4.8%. On the other hand, cooling energy consumption remains constant.

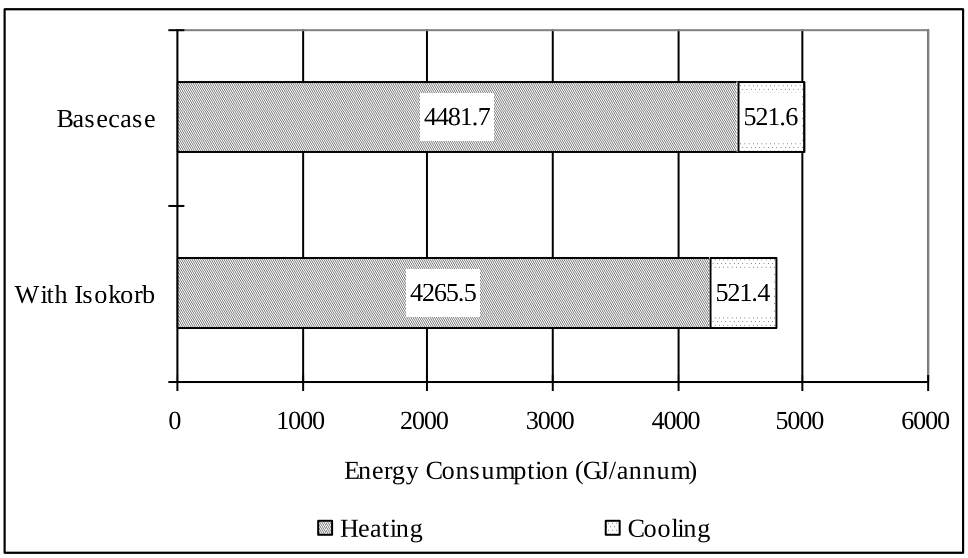

Figure 22 –Building's heating and cooling energy consumption with Isokorb system

3.4.7 Insulated Concrete Forms

Four Insulated Concrete Form (ICF) configurations were investigated to determine their relative energy performance (Table 7). The chosen ICF systems all have a higher insulation value than the as-designed precast insulated concrete panels, which is currently at RSI 2.41 (R 13.7). As expected, in all four cases, heating energy consumption decreases as thermal resistance increases (Fig. 23). By incorporating ICF-1, -2, -3, and -4 into the building's exterior wall, heating energy consumption of the building would be reduced by approximately 2.6% for ICF-1, -2, an -3, and 4.3% for ICF-4; cooling energy consumption on the other hand is reduced by approximately 1.7% for ICF-1, 1.3% for ICF-2, 0.8% for ICF-3, and 1.3% for ICF-4. ICF-1 performs slightly better than ICF-2 and -3 as simulation results show that ICF-1 achieves the biggest reduction in both heating and cooling energy consumptions. All three configurations have the same R-value and material thickness and the difference in performance is due to the thermal capacitance of the external wall. However, the difference between the three configurations might be too small to conclude any significant savings with manipulating the configurations. The total energy consumption is reduced by approximately 2.4 % for ICF-1 to -3, and by 4.0% for ICF-4.

Table 7 - Wall configurations under investigation

Wall ID	Configuration (interior insulation + concrete + exterior insulation)	Thickness (mm)	RSI	R
ICF-1	25 + 200 + 75 mm	300	2.85	16.2
ICF-2	50 + 200 + 50 mm	300	2.85	16.2
ICF-3	75 + 200 + 25 mm	300	2.85	16.2
ICF-4	62.5 + 200 + 62.5 mm	325	3.47	19.7

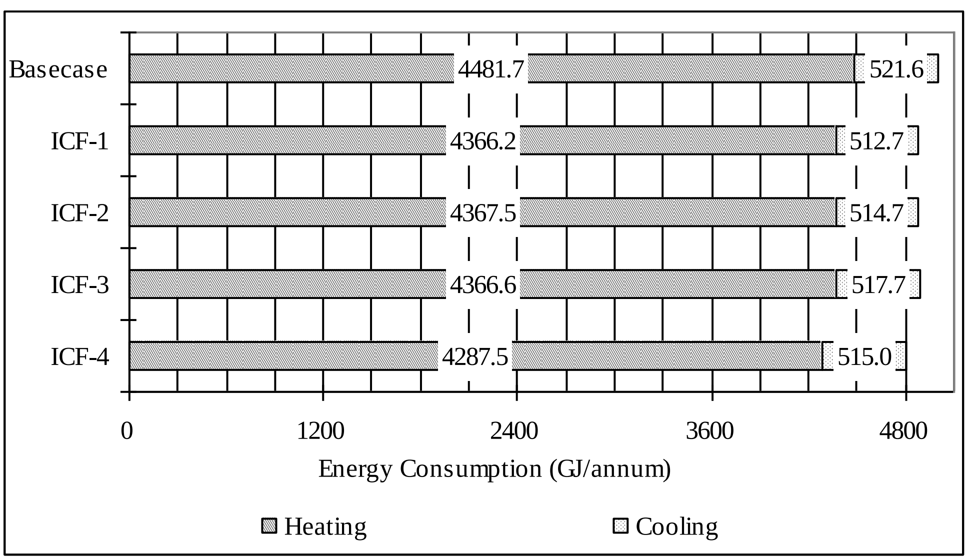

Figure 23 - Effects of ICF configurations on Building's heating and cooling energy consumption

3.4.8 Overhangs

The as-designed building consists of balcony structures that span approximately 52% of the building perimeter. These balcony structures extend 1.9 m from the exterior wall. To evaluate the effectiveness of the as-designed balconies in shading unwanted solar heat in the summer, simulation was performed on the building without the as-designed balconies. As well, a series of simulations were performed by incorporating exterior overhang structures at 0.5m increments. Simulation results (Fig.24) show that although the as-designed balcony structures are able to reduce the cooling energy consumption by 20.6% when compared to the Basecase with no balconies, heating energy consumption is increased by 5.9% and the combination results in an increase of total energy consumption by 2.3%. Installing overhang structures can help reduce solar heat gain during cooling seasons. Reductions of 18.1% to 28.4% in cooling energy consumption are recorded; with 2m overhang structures achieving the largest reduction. However, as overhang structures are in place, the admittance of passive solar heat gain desired for heating seasons is affected and leads to an increase of heating energy consumption. An increase of 5.2% to 9.2% is recorded.

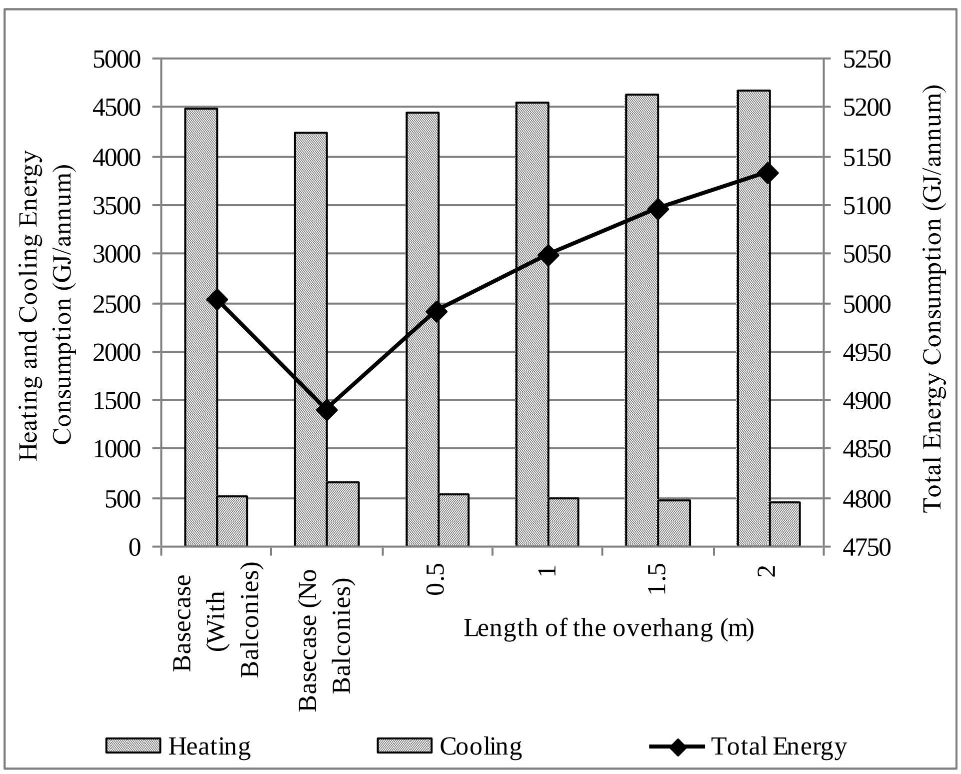

Figure 24 - Effect of external window overhang structures on Building's heating and cooling energy consumption

3.4.9 Window configurations

Perrson et al. (2006) studied the impact of window orientation to the space heating and cooling demand in Sweden and concluded that north-facing windows have the largest impact on space heating load, followed closely by east- and west-facing windows respectively. On the other hand, space cooling demand was impacted by west-facing windows the most, followed by east-, and south-facing windows respectively. Her study also found that the influence of east- and west- facing windows on space heating and cooling demand does not differ noticeably. Straube and Burnett (2005) illustrated that east- and west-facing windows receive 40% more solar heating than south-facing windows on July 21st at 45' north latitude (Toronto is at 43'40" north latitude). On the other hand, on January 21st, south-facing windows receive approximately 3.6 times the solar heating east- or west-facing windows receive, and 15 times the solar heating north-facing windows receive. Lechner (2009) illustrated that all orientation except south receive maximum solar radiation in summer.

Previous research on low-energy buildings with building energy analysis generally investigated the performance of installing the same glazing system in all orientations and neglected to study the potential benefits of installing different glazing systems in different orientations. From previous studies (Persson at al., 2006; Straube & Burnett, 2005; Lechner, 2009), six window configurations with four types of windows were evaluated in this study. In Configuration 1, EnergyStar certified windows (SHGC: 0.44, U-value: 1.5W/m^2K) are used in north-facing walls only. In Configuration 2, in addition to using EnergyStar certified windows in north-facing walls, east-, and west-facing walls are also equipped with EnergyStar certified windows. Configuration 3 is same as Configuration 2, but with east-, and west- facing windows also equipped with high SHGC (0.568). In Configuration 4, south-facing walls are also equipped with EnergyStar certified windows. Configuration 5 is very similar to Configuration 4 but with south-facing windows also equipped with high SHGC. Configuration 6 aims to reduce unwanted solar heat gain during cooling seasons and uses spectrally selective windows (SHGC: 0.274, U-value: 1.34W/m^2K) in west-facing windows. The configurations are as summarized in Table 8.

Table 8 - Window configurations

Configuration ID	***North-facing*** U-value (W/m^2K)	SHGC	***East-facing*** U-value (W/m^2K)	SHGC	***South-facing*** U-value (W/m^2K)	SHGC	***West-facing*** U-value (W/m^2K)	SHGC
Basecase	2.27	0.44	2.27	0.44	2.27	0.44	2.27	0.44
Configuration -1	1.5	0.44	2.27	0.44	2.27	0.44	2.27	0.44
Configuration -2	1.5	0.44	1.5	0.44	2.27	0.44	1.5	0.44
Configuration -3	1.5	0.44	1.5	0.568	2.27	0.44	1.5	0.568
Configuration -4	1.5	0.44	1.5	0.568	1.5	0.44	1.5	0.568
Configuration -5	1.5	0.44	1.5	0.568	1.5	0.568	1.5	0.568
Configuration -6	1.5	0.44	1.5	0.568	1.5	0.568	1.34	0.274

The EnergyStar certified windows are Argon gas filled , double glazed units, consisting of outer pane of 10 mm thick clear glass and inner pane of 6mm Ti-R glass with low-E coating. DesignBuilder (DB) calculated the SHGC to be 0.44 and U-value was set to be 1.5 W/m^2K.The EnergyStar certified windows with high SHGC are Argon gas filled (13mm), double glazed units, consisting of outer pane of 6 mm thick clear glass with low-E coating and inner pane of 6 mm thick glass. DB calculated the SHGC to be 0.568 and U-value to be 1.5 W/m^2K. The spectrally selective windows are argon gas filled, double glazed units, consisting of outer pane of 6mm thick spectrally selective tinted glass and inner pane of 6mm thick clear glass. U-value and SHGC were calculated to be 1.34 W/m2K and 0.274. All windows are framed with Aluminium. The effect of replacing the existing window system with the above window configurations was investigated (Fig. 25-26). As shown in Fig. 26, there exists a net heat loss through the glazing for Basecase and Configuration 1. Heat flow is calculated to be the difference of conduction heat loss and heat gain through the glazing system. In general, the amount of heat gain increases as the performance of the windows improves from Configuration 1 to 6, except for the case with Configuration 5 to Configuration 6. Net positive heat gains are resulted for Configuration 2 to 6 as solar heat gain through the glazing systems increases.

As the north-facing windows were replaced with EnergyStar certified windows from Basecase to Configuration 1, the heat loss through external glazing is reduced by 6.4% and solar gain through windows is decreased negligibly from Basecase to Configuration 1. This results in a reduction of 2.7% for heating energy consumption and a 1.1% increase for cooling energy consumption.

As windows from the north, east, and west orientations were replaced with EnergyStar certified windows from Basecase to Configuration 2, the heat loss through external glazing is reduced by 37.2%, which is much more significant than just replacing north-facing windows. The amount of conductive heat loss through windows is approximately the same in north-facing and east- or west-facing windows (Lechner, 2009), and since the building is oriented such that the long sides faces east and west, replacing windows on the east and west walls would have a more pronounced impact on the heat balance. Similar to Configuration 1, the amount of solar heat gain through windows differs negligibly as better insulated windows are installed. As a result, heating and cooling energy consumption is reduced by 14.8% and 5.3% respectively when compared to Basecase.

Configuration 3 is similar to Configuration 2, but with east- and west-facing windows also equipped with high SHGC (0.568). With higher SHGC on the east- and west-facing windows, a significant increase of solar gain through the windows is recorded according to the simulation results. The amount of solar gain through the windows is increased by approximately 20.4% throughout the year. The amount of heat loss through glazing on the other hand is reduced by approximately 26.9% when compared to Basecase. The combination of decreased glazing heat loss and increased solar heat gain through glazing results in a decrease of heating energy consumption of 17.0% from Basecase. During the summer, the increased amount of solar gain causes the cooling energy consumption to increase significantly by 12.5%. While the high solar heat gain glazing system is effective in allowing more passive solar heat into the space during winter heating seasons, the lack of effective shading devices causes the cooling energy consumption to be increased significantly when compared to Basecase. This leads to a reduction of total energy consumption by 13.9% when compared to Basecase.

Configuration 4 is similar to Configuration 3, with south-facing windows also be replaced with EnergyStar certified windows. The impact of this upgrade is not as significant as all the previous cases. The amount of heating energy consumption is decreased by approximately 3.8% from Configuration 3 with cooling energy consumption remains constant. Generally, when designing passive buildings, a common technique is to place large glazed areas oriented to the south to maximize solar heat gain during the winter. The south-facing EnergyStar certified windows were equipped with higher SHGC in Configuration 5 to maximize solar heat gain. Solar gain is increased by 5.3% from Configuration 4, which leads to a drop of heating energy consumption of merely 1.2% but an increase of cooling energy consumption of 4.2%. The combination of the reduction of heating energy consumption and increase of cooling energy consumption leads to a net decrease of total energy consumption for heating and cooling of merely 0.4% from Configuration 4. For Configuration 6, spectrally selective windows are used in the west-facing wall to reduce unwanted solar heat gain during the summer. Similar to Configuration 5, north-, east-, and south-facing walls are installed with energy-efficient windows. East- and south-facing windows are still equipped with a higher solar heat gain coefficient. With just replacing the west-facing windows to spectrally selective windows, transmitted solar energy is reduced by 17.6% from Configuration 5. The heating energy consumption is reduced by 17.5% with this configuration and cooling energy consumption is increased by only 1.3% compared to Basecase, a 13.8% drop from Configuration 5.

The benefits of installing more advanced windows on different orientations are made clear with the above discussions. The decision on which configuration to incorporate is a trade-off between cost and performance. Fig. 26 illustrates the heating and cooling energy consumption reduction for all configurations. Although Configuration 5 achieves the biggest reduction in heating and cooling energy consumption at 17.1%, one can argue that the additional investment might not justify the marginal reduction.

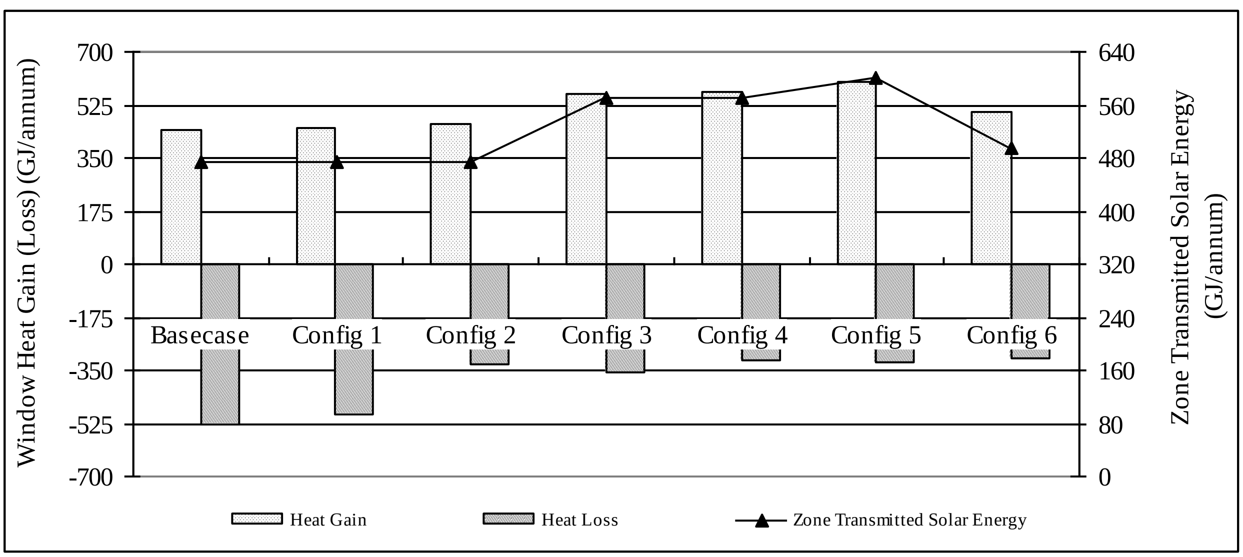

Figure 25 – Heat gain (loss) and transmitted solar energy with varying window configurations

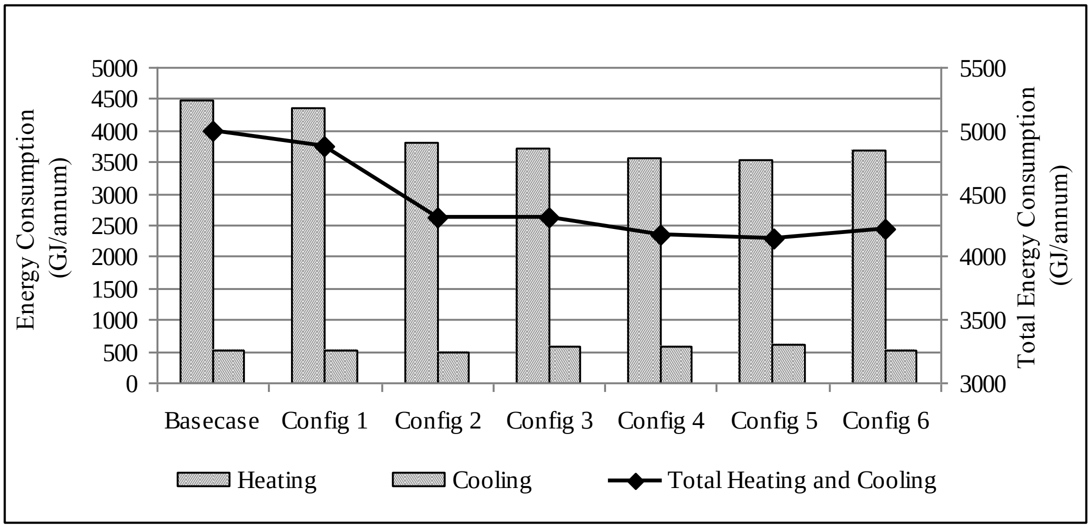

Figure 26 - Effects of window configurations on Building's heating and cooling energy consumption

3.5 Concluding remarks

The energy performance of a 12-storey MURB in Toronto under schematic design phase was investigated using the detailed thermal simulation tool, EnergyPlus. The simulation results indicate a large potential to reduce the energy consumption in this MURB by employing certain envelope strategies described in this study. Clearly, conduction of a thermal simulation study allows recognition of the energy conserving strategies, which would be otherwise disregarded. The benefits of installing different types of advanced glazing systems on different orientation are made clear. It can be suggested that the energy consumption of this MURB is more sensitive to window R-values than wall R-values. When R-value of the exterior wall was increased from Basecase at 2.47 m2K/W to 3.92 m2K/W, or 58.7%, heating energy consumption drops 4.5% and cooling energy consumption remains constant. However when the R-value of windows on the east-, west-, and north-facing walls were increased from Basecase at 0.44 m^2K/W to 0.67 m^2K/W, or 51%, heating and cooling energy consumption drops 14.8% and 5.3% respectively. The provisions of exterior windows shades and thermal break system for the concrete to concrete connection of the free cantilever balconies were able to reduce the total heating and cooling energy consumption quite considerably, by up to 8.2% and 4.3% respectively.

As well, the usage of the thermal simulation tool helped recognized certain rules for energy-efficient designs might not be applicable in all circumstances. Blindly adopting energy conservation measures might potentially result in a building with higher operating cost. For instance, increasing the R-value of the exterior wall gives diminishing returns on the reduction of heating energy consumption. Cooling energy consumption on the other hand remains fairly constant as insulation thickness is increased, which is in contrary to the widely accepted norm that wall insulation helps reduce annual energy consumption for heating and cooling. Manipulating the thermal mass of the exterior wall does not yield significant reductions in either heating or cooling energy consumption. The findings on exterior wall R-value and thermal mass signifies that it is important to integrate insulation with other passive strategies such as shading, natural ventilation and glazing design to reduce the cooling energy consumptions. Simply adopting rules for energy-efficient designs might not be applicable in all circumstances, and therefore should be subjected to comprehensive reviews in a case-by-case basis. The thermal simulation study also identified some of the strategies investigated are less effective than expected, namely changing the color of the wall surface, manipulating the thermal mass of the exterior wall, and provisions of overhang structures.

The thermal simulation study also signifies the potential of improving air-tightness in reducing energy consumption. The air-tightness level of the building affects the heating energy consumption significantly by up to 35.5% with air-tightness reduced from 0.4 ACH to 0.1 ACH. The impact of improving the air-tightness of the building on the heating energy consumption of the building is far more superior to many of the strategies described in this study, and thus it might be worthwhile for current building certification programs such as LEED to integrate the impacts of improving air-tightness into their accreditation programs so as to encourage better building practises and increase energy efficiency of buildings.

Simulation results show that significant energy reduction can be achieved with varying building envelope characteristics. Since it is during the schematic design phase, changes to the architectural design and layout might be made constantly. It is important to be aware of any major design changes on the building geometric details throughout the process and these changes should be reflected in the simulation model accordingly. Mechanical and electrical design specifications from design briefs and meetings have to be gathered and incorporated into the simulation model. Although the process in gathering the above information might be time-consuming and resource intensive, it is imperative in establishing a realistic thermal simulation model that would closely resemble the actual building being designed.

This simulated study would not only improve the energy efficiency of the subjected building, but would also provide architects with the knowledge necessary to change their accepted standard practices for MURB design to deliver improvements in energy-efficiency of this group of buildings. It is important to note that however, the combination of some strategies might yield synergy, or in some cases antagonism with not only strategies being considered in this study, but also other building strategies such as maximizing the benefits of daylighting. For instance, simulation result shows that the incorporation of internal shades can effectively reduce cooling load during the summer days, however the incorporation of such strategy will severely affect the availability of daylighting which can be otherwise utilized. Sets of simulations incorporating different groups of strategies should be conducted to predict overall building performance for each case and decisions should be made based on the collective performances of strategies. Whenever possible, thermal simulations should be coupled with other simulation programs such as those that can optimize daylighting, mechanical systems, and potential of natural ventilation, etc. to generate a more holistic view on the energy performances of building designs.

4. Application of thermal simulations during the post-occupancy phase

4.0 Introduction

The previous chapter illustrated the potential benefits thermal simulation can bring to the building energy performance during the schematic design phase. This chapter will demonstrate the usage of thermal simulation programs during the post-occupancy phase in potentially improving the thermal comfort of occupants as well as reducing energy consumptions.

In most construction projects, buildings do not get systematically reviewed after the projects have been completed. Typically, both design teams and clients do not tend to evaluate if the building constructed meets its design objectives, such as those related to thermal comfort and energy consumptions. Members of the design teams such as architects and engineers are generally reluctant to reflect on their design because there is a lack of incentive to do so and can potentially pose professional liability for the owners and occupants. The owners on the other hand, may not perceive the importance of systematically evaluating the building's performance, or simply are not aware of potential benefits the process can bring to their well-being and property value. Together with external factors such as the lack of government support and relatively low fuel cost, existing buildings are hardly ever subjected to comprehensive evaluations.

However, buildings constructed might not be performing as well as they should. Buildings being designed and constructed are often subjected to the inherent repetitive implementation of design solutions, such as those related to floor plan configurations, and mechanical and electrical layouts, etc., and might not take specific site factors into account (Wong et al., 2000).

A study conducted by Petersdorff et al. (2004) has shown that a 60% reduction in total EU-15 CO_2 emissions can be accomplished if retrofit measures covered by the Directive on Energy Performance of Buildings, the EPB directive (2002/91/EC) (Department of Finance and Personnel, 2002) are implemented to all existing commercial and residential buildings in EU-15.

4.1 Thermal simulation studies as part of post-occupancy evaluations

The conventional building delivery process usually ends after the building is finished construction and occupants moved in the building (Fig. 1). And in most cases, the building would not get systematically reviewed throughout its entire life span. This hinders the opportunity for occupants, whom are the end-users to be involved in the life-cycle of the building.

Commissioning has been used as one of the options in validating building designs. According to ASHRAE Guideline 0-2005 “The Commissioning Process”, commissioning is defined as, “A quality focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements.” It is a formal and rigorous quality control process where it involves the delivery of preventive and predictive maintenance plans, and preparation on specific operating manuals and provision of trainings for building operators to follow. In essence, the process formalizes review in ensuring the project design objectives are met throughout the entire life-cycle of the design process, from planning, to design, to construction, and occupancy phases. This is fulfilled by carrying out inspection and functional performance testing, and supervising the building operators’ training and record documentation.

Though the regular commissioning process is an imperative procedure for verifying that all of the building systems perform as they were designed and meet the operational needs of the owner, it generally does not have a focus on the integrated nature of building systems and how it interacts with the building occupants. In recognizing this, the industry has started to adopt processes that could systematically review a completed building or a group of buildings that have similar layouts and operations. The processes could consist of monitoring environmental conditions such as temperature, humidity, lighting levels, and acoustics, assessing energy consumptions, or acquiring feedback from occupants through interviews or surveys. The adoption of one or a combination of the above processes can generally be recognized as a post-occupancy evaluation (POE). Other terminologies used to refer to similar processes include continuous commissioning for commercial and institutional buildings and central plant facilities (Liu et al., 2002), and energy performance evaluation (Pless & Torcellini, 2004), etc. An important distinction from POE to the regular commissioning process is that POE focuses on optimizing system operations for existing building conditions, rather than validating building system designs for new buildings.

This research project illustrates the potential benefits of incorporating thermal simulation studies as part of POEs (Fig. 2). POE usually commence by obtaining occupant feedback through interviews or surveys. Though their opinions concerning indoor environmental quality (IEQ) are by nature subjective, they are nevertheless essential to understanding how well a building performs (Gonchar, 2008). This provides the first step in the feedback loop. This step is essential in help assessing the completed building and its performance in use, and to help identify deficiency in existing buildings. At this step, thermal simulation can contribute to evaluating the extent of the deficiency. In order to do so, information on the existing building such as HVAC equipment specifications, building envelope configuration, operational schedules, etc. of the existing building have to be gathered to help construct an accurate simulation model that would reflect the existing building's performance. Calibration is essential in fine-tuning the simulation program with recorded data, and detailed energy building analysis can proceed afterwards. With deficiencies identified by studying the comments provided by occupants and the thermal simulation results, investigation of mitigation strategies will proceed. At this step, thermal simulation can contribute to evaluating strategies. Simulation results are then reviewed and modifications to design strategies are proposed if needed.

4.2 Perceived problems with existing systems built today

In the year of 2008, more than 100 000 single-detached houses were built in Canada, more than 45% of which were in the province of Ontario. The heating and cooling loads of these houses are generally overestimated, which is partly due to the common practice of utilizing single-zone constant air volume (CAV) HVAC systems for conditioning the entire house (Redfern, 2006). These systems rely on one temperature sensor installed at one location to depict whether heating or cooling is required for the entire house. This typically results in inefficient heating or cooling due to the differences in thermal load in different spaces throughout the house (Redfern, 2006; Wang & Jin, 2000). This in turn reduces the thermal comfort of occupants as well as wasting energy used for conditioning unoccupied spaces. However, such systems are being widely installed in new developments for past decades as the industry does not perceive a need to change and the norm is to evaluate designs with first-cost, rather than life-cycle costs (CMHC, 1996). Numerous researches have shown that improving thermal comfort and reducing energy consumed by HVAC systems is achievable with advanced control mechanisms (Liang & Du, 2005; Kulkami & Hong, 2004; Freire et al., 2008; Dounis & Caraiscos, 2009). There is a need to evaluate the potential deficiency of such systems before improvements can be readily realized on a large scale and more advanced systems can become the norm.

4.3 Survey

As mentioned, obtaining feedback from occupants is imperative in help identifying potential deficiencies in existing buildings. To identify potential energy savings and improvement to thermal comfort in residential houses, today's situation was investigated first. The investigation was carried out in two parts, an on-site interview and a full scale survey.

For the first part, 15 respondents were interviewed at their dwellings in December, 2008. The objective of the interviews was to gather information on mechanical equipment specifications and to collect necessary information to help create a shortlisted set of questions to be included in the full scale survey. A typical house was selected and was used as the subject of the thermal simulation. In order to help calibrate and validate the simulation model, temperature and humidity level in four rooms, namely kitchen, family room, master bedroom, and study room, and the power output of the central furnace were recorded for a period of three months, from January to March, 2009. The floor plan and the envelope configuration of the house, and operational schedules were gathered from the occupant. Through the interviews, problems were identified with the lack of controllability and the occurrences of overheating in winter heating months. In order to generate a more holistic view on the problem and to provide a statistically supported analysis, it is necessary to conduct a full scale survey to evaluate the extent of the problems.

Following the interviews, a full-scale survey was conducted with Ontarioians residing in low-rise residential buildings and a provincially representative sample was gathered. The main objectives of the full scale survey are as follows:

- To identify on potential deficiencies in the existing building stock by investigating the thermal comfort conditions of occupants
- To analyze factors that impact on thermal comfort levels
- To investigate occupants' energy consumption behaviours specifically related to the control of their thermal environment

4.3.1 Methods

The selection of the sample size (n) was based on Eq. (1) (Cochran, 1963), which defines the relationship between the confidence interval, the degree of variability, and the margin of error of sample proportions.

$$n = \left(\frac{Z_a\sqrt{p(1-p)}}{ME_p}\right)^2 \quad (1)$$

A margin of error (ME_p) of 5%, degree of variability (p) of 0.5, and a 95% confidence interval was selected for the purpose of this study. A degree of variability of 0.5 indicates the maximum variability in a population and is used to determine a more conservative sample size. Solving Eq. (1) results in an n of 385.

The list of questions included in the survey is as attached in Appendix A. The survey is targeted to residents in low-rise residential buildings in Ontario, Canada. The questionnaire consisted of three sections: demographic information, satisfaction and controllability over room temperature, and heating system setup and operation. In the first section, respondents were asked to provide information about themselves and their dwellings, such as age and sex of the respondent, type, age, and size of the dwelling, etc. In the second section, respondents were asked to rate their satisfaction and controllability over their room temperature, as well as the frequency they experience overheating or overcooling in heating and cooling seasons respectively. The last section asked respondents to provide details on their heating system operation and configuration.

4.3.2 Statistical method

Statistical analyses were performed with non-parametric statistical tests. Chi-square ($I?^2$) tests of significance Eq. (2) were performed to evaluate the existence of relationships between nominal and ordinal data and between nominal pairs. The calculated $I?^2$ is then evaluated with table of the chi-square distribution. Cramer's V, Eq. (7) was determined to evaluate the strength of correlations. Table 9 illustrates the scale for interpreting the calculated Cramer's V value.

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{c}\frac{(O_{ij}-E_{ij})^2}{E_{ij}} \qquad DF = (i-1)(j-1) \tag{2}$$

Where i = row, j = column. E_{ij} , n_i , C_j , and N is defined as Eq. (3) – (6) below

$$E_{ij} = \frac{n_i C_j}{N} \tag{3}$$

$$n_i = O_{i1} + O_{i2} + \cdots + O_{ic} \tag{4}$$

$$C_j = O_{1j} + O_{2j} + \cdots + O_{rj} \tag{5}$$

$$N = n_i + n_2 + \cdots + n_r \tag{6}$$

With $DF = (i-1)(j-1)$

$$V = \sqrt{\frac{\chi^2}{n(m-1)}} \tag{7}$$

Table 9 - Interpretation of calculated Cramer's V (Rea, 2005)

Measure	Interpretation
0.80 to 1.00	Very strong association
0.60 and under 0.80	Strong association
0.40 and under 0.60	Relatively strong association
0.20 and under 0.40	Moderate association
0.10 and under 0.20	Weak association
0.00 and under 0.10	Negligible association

For ordinal pairs, Kendall's tau-c was determined to evaluate the existence of relationships and Gamma coefficients were calculated in assessing the correlation strength. Table 10 illustrates the scale for interpreting the calculated Gamma value. The significance level of difference was set at 5% (p<0.05).

$$tau - c = (N_c - N_d)\left[\frac{2m}{n^2(m-1)}\right] \tag{8}$$

$$p\ (upper - tailed) = P\left(Z \geq \frac{(N_c - N_d - 1)\sqrt{18}}{\sqrt{n(n-1)(2n+5)}}\right) \tag{9}$$

$$\gamma = \frac{N_c - N_d}{N_c + N_d} \tag{10}$$

With operations on N_c **and** N_d **as follows** :

$$N_c = N_c + 1, \qquad if\ \frac{Y_j - Y_i}{X_j - X_i} > 0$$

$$N_d = N_d + 1, \qquad if\ \frac{Y_j - Y_i}{X_j - X_i} < 0$$

$$N_c = N_c + \frac{1}{2}\ and\ N_d = N_d + \frac{1}{2}, \qquad if\ \frac{Y_j - Y_i}{X_j - X_i} = 0$$

$$no\ comparsion\ if\ X_j = X_i \tag{11}$$

Table 10 – Interpretation of calculated Gamma (Rea, 2005)

Measure	Interpretation
± 1	Perfect association
± 0.75 to ± 0.99	Very strong association
± 0.60 to ± 0.74	Strong association
± 0.30 to ± 0.59	Moderate association
± 0.10 to ± 0.29	Low association
± 0.01 to ± 0.09	Negligible association
0	No association

Mann-Whitney (Eq. (12) – (14)) and Kruskal-Wallis (Eq. (15) – (18)) tests were performed to evaluate group differences on ordinal (ranked) data. Exact p-values for nonparametric tests were reported rather than the asymptotic p-values. This is due to the limitations of asymptotic p-values with samples with skewed distributions (Kinnear & Gray, 2006).

$$p - value = 2 \cdot P\left(Z \leq \left[T(or\ T') + \frac{1}{2} - n\frac{N+1}{2}\right]\frac{1}{\sqrt{\frac{nm(N+1)}{12}}}\right) \quad (12)$$

T from Eq. (13) is used if there are no or just a few ties between the ranks; in the event of many ties, T' from Eq. (14) is used.

$$T = \sum_{i=1}^{n} R(X_i) \quad (13)$$

$$T' = \left[T - n\frac{N+1}{2}\right]\frac{1}{\sqrt{\frac{nm}{N(N-1)}\sum_{i=1}^{n} R_i^2 - \frac{nm(N+1)^2}{4(N-1)}}} \quad (14)$$

$$T = \frac{1}{S^2}\left\{\sum_{i=1}^{k}\frac{R_i^2}{n_i} - [N(N+1)^2]\frac{1}{4}\right\} \quad (15)$$

$$S^2 = \frac{1}{N-1}\left\{\sum_{\text{all ranks}} (R(X)_{ij})^2 - [N(N+1)^2]\frac{1}{4}\right\} \quad (16)$$

$$N = \sum_{i=1}^{k} n_i \quad (17)$$

$$R_i = \sum_{j=1}^{n_i} (R(X)_{ij}) \quad (18)$$

where $[R(X]_{ij})$ represent the rank assigned to $[(X]_{ij})$ and R_i be the sum of the ranks assigned to the *i*th sample.

4.3.3 Sample population distribution

The survey was planned to target low-rise residential buildings that would represent typical types and demographics of the Ontario population. A total of 519 surveys were collected from April to June 2009 and 396 of which were completed and provided valid data. Only those that were completed were included as part of the statistical analysis. Summaries of the respondents are given in Table 11. It shows that the sample population distribution corresponds fairly well with Ontario population. Out of the 396 respondents, 67.4 % resides in single-detached houses and 23.7% and 8.9 % of which resides in double/row houses and low-rise MURBs respectively. This is comparable to the provincial distribution, according to the 2006 census (StatsCan, 2006), 66.9% of Ontarioians resides in single-detached houses, and 20.3% and 12.9 % of which resides in double/row houses and low-rise MURBs respectively. The median age of Ontario's population is 39, when compared to 33 for the survey population. 61.2% of the surveyed dwellings were built before the year of 1986 and 38.8% were built after the year of 1986. While 68.6% of Ontario dwellings were built before the year of 1986 and 31.4% were built after that year. 81.2% of the occupants own the property and 18.8% are renting. Distributions between males and females have also been respected.

Table 11 – Summary of sample

		All	Dwelling Type		
			Single-Detached	Double/Row Houses	Low-rise MURBs
Gender (%)	Male	50.6	52.4	48.4	44.1
	Female	49.4	47.6	51.6	55.9
Ownership (%)	Own	81.2	88.7	75	45.5
	Rent	18.8	11.3	25	54.5
Age (yr)	Mean	35.49	36.4	33.5	33.8
	SD	12.50	13.0	11.1	11.7
	Minimum	16	18	16	19
	Maximum	68	68	66	59
Year of Construction (yr)	Mean	1971.5	1971.3	1969.5	1979.0
	SD	31.3	30.3	33.7	32.7
	Minimum	1856	1856	1865	1865
	Maximum	2009	2009	2007	2008

4.3.4 Results and discussion

4.3.4.1 Thermal comfort and controllability over room temperature

ASHRAE Standard 55-2004 (ASHRAE, 2004) specifies conditions where 80% of the building occupants are expected to express satisfaction over their thermal environment. Although the subjected building types are not expected to comply with the above comfort standard, the 80% acceptability threshold can act as a reference to this study. Results show 6.4 % and 13.3 % of the respondents are very dissatisfied and dissatisfied respectively with their room temperature in the winter. Satisfaction with room temperature was rated with a scale from 1 to 5 with 1 being very dissatisfied and 5 being very satisfied and results reveal that 5.9% and 14.5% of the female respondents and 6.3 % and 12.0% of the male respondents feel very dissatisfied and dissatisfied (Fig. 27). The acceptability at 80% is not met with female respondents as 20.4% expressed dissatisfaction with their thermal environment; while on the other hand, the threshold is barely met with male respondents, as 18.3% expressed dissatisfaction with their thermal environment. Although male respondents are relatively more satisfied than female respondents, a Mann-Whitney U test failed to show significance: $p > 0.05$ (two-tailed). This corresponds to Donnini et al. (1997), where the difference in thermal requirement of both sexes is minimal in office environments, but does not correspond to Wang (2006), where he found that males are less sensitive to temperature variations than females and that the neutral operative temperature of males is 1^{o}C lower than that of females. The method used to investigate thermal acceptability in the present study is based on a five point scale also employed in Karjalainen (2008). Yang & Zhang (2008) used three methods to investigate thermal acceptability and yields distinctive results. Although it can be argued that employing different methods of assessing thermal comfort levels would produce diverse results, the five point scale used in this present study is chosen due to its simplicity and its ordinal nature, which enable relationships to be evaluated between other variables using the selected non-parametric tests.

There are differences in satisfaction between different types of dwellings (Fig. 28). 20.4%, 15.7%, and 23.5% of the residents feel dissatisfied or very dissatisfied with the room temperature for single-detached, double/row houses, and low-rise MURBs respectively. As seen, the 80% acceptability threshold is not met with respondents residing in single-detached and low-rise MURBs. The Kruskal-Wallis test reveals insufficient differences to achieve significance between the three types of dwellings: $p > 0.05$.

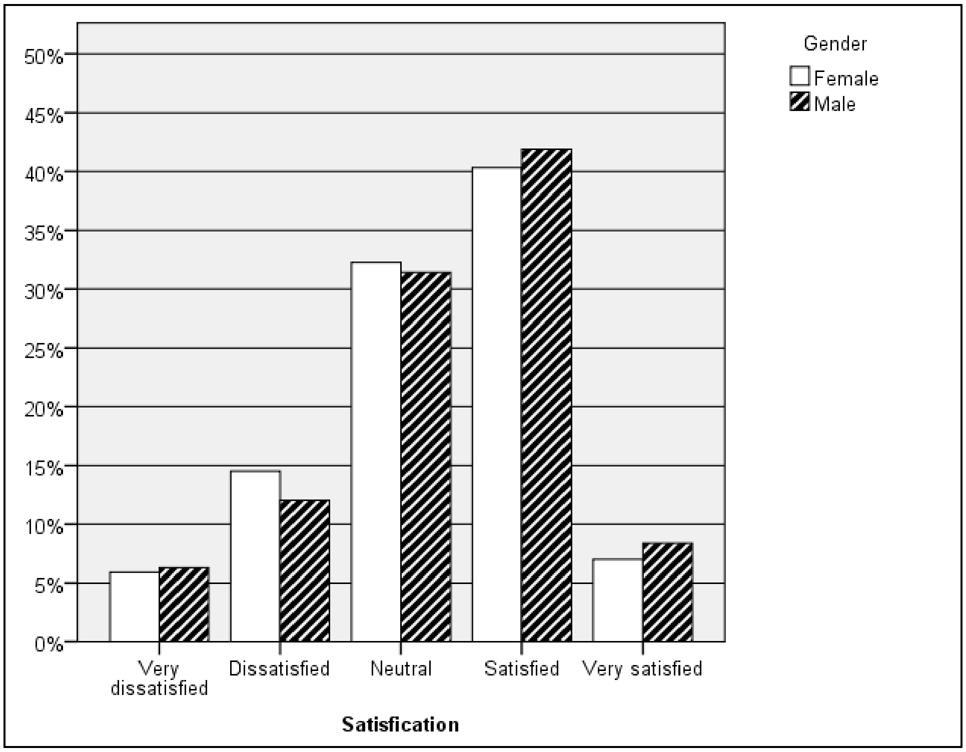

Figure 27 - Satisfaction with room temperature for male and female respondents

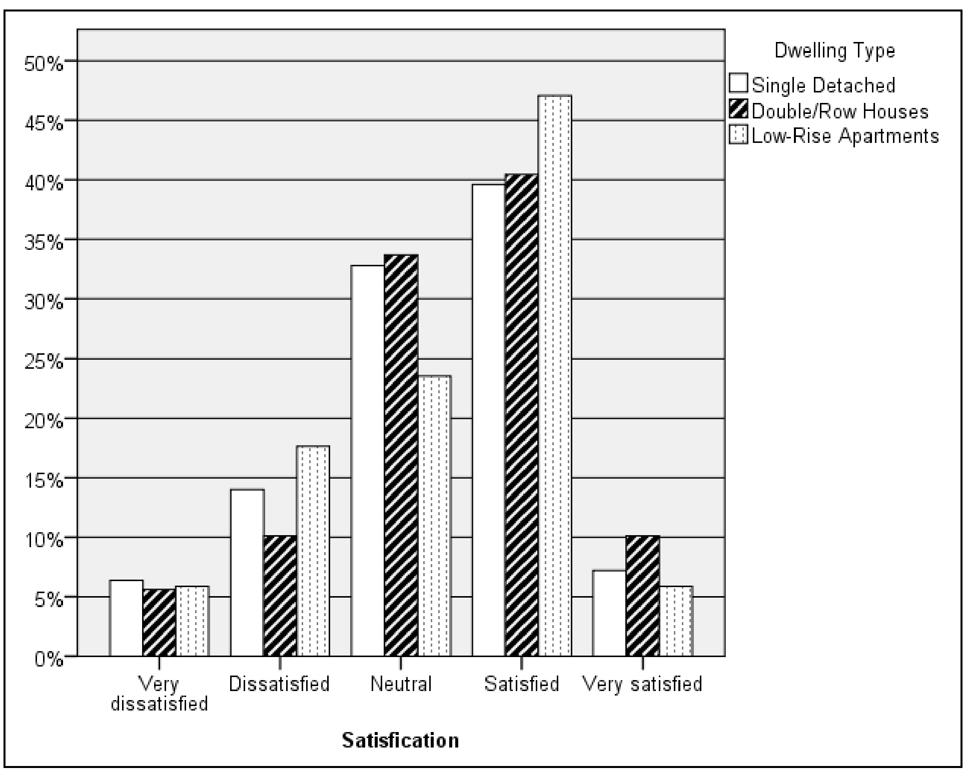

Figure 28 - Satisfaction with room temperature for different house types

The respondents were asked to rate their controllability over room temperature in winter with a scale from 1 to 5 with 1 being very badly and 5 being very well. Controllability is the extent to which a respondent feel they can control their room temperature. Results show that 2.6 % and 10.0% of the respondents rate their controllability as very badly and badly respectively (Fig. 29). There exists a difference between male and female respondents, 12.0% and 14.2 % of the female and male respondents rated their controllability as badly or very badly. A Mann-Whitney U test failed to show significance: $p > 0.05$ (two-tailed). Results also reveal that 12.1%, 11.3%, and 26.5% of the respondents rate their controllability over room temperature as badly or very badly in single-detached, double/row houses, and low-rise MURBs respectively (Fig. 30). The Kruskal-Wallis test reveals insufficient differences to achieve significance between the three types of dwellings: $p > 0.05$.

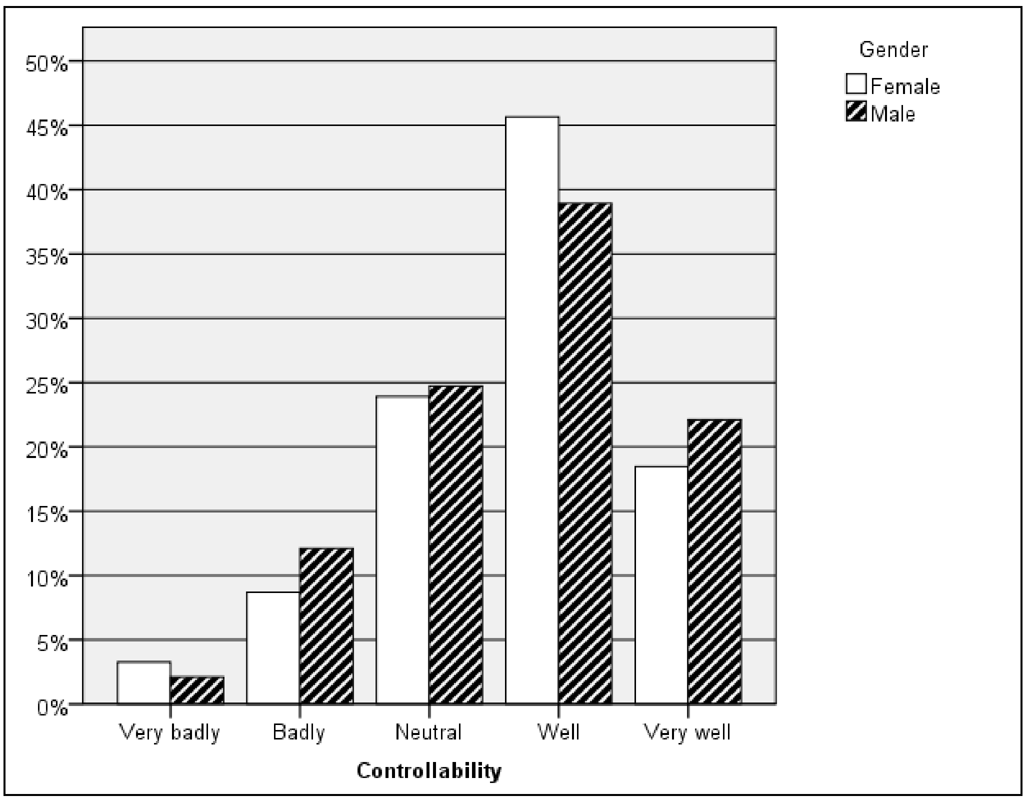

Figure 29 - Controllability with room temperature for male and female respondents

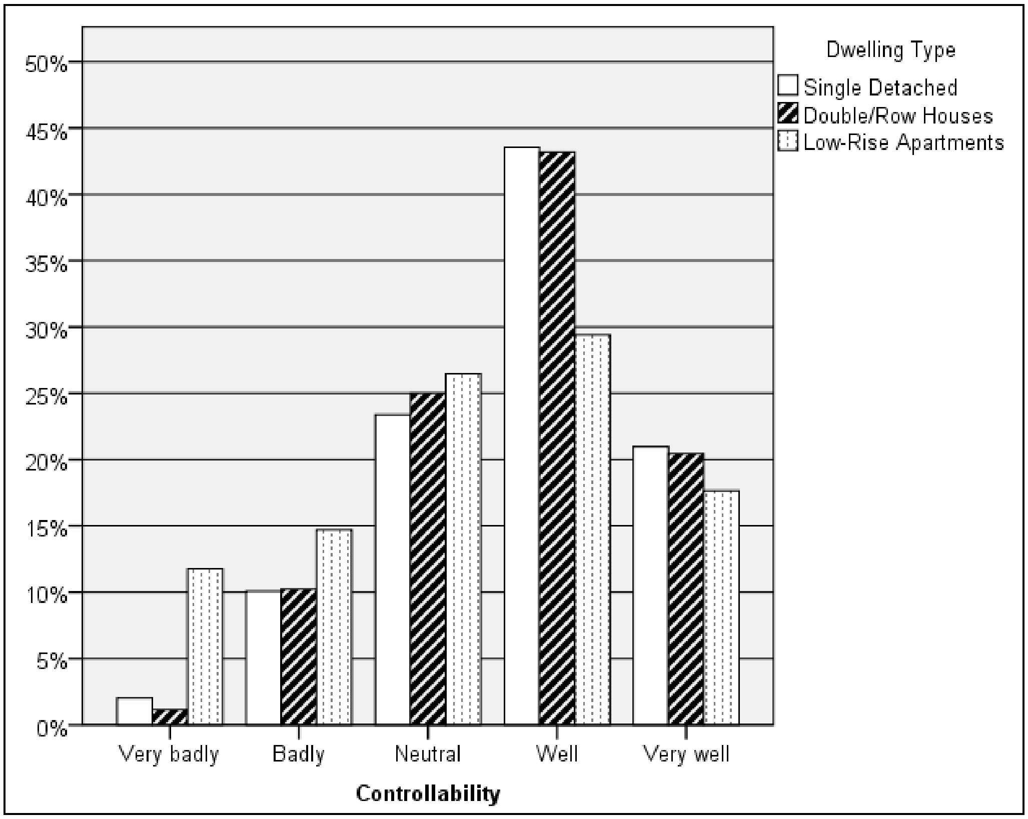

Figure 30 - Controllability with room temperature for different house types

Results reveal a moderate correlation between controllability and thermal comfort. Using Kendall's tau-c test and gamma correlation coefficient, the strength of association is moderate: p=0.00, γ =0.43. This is consistent with Karjalainen (2008) and Wagner (2007) studies, for which Karjalainen (2008) found a strong association between thermal comfort and controllability in Finnish dwellings. This shows that building occupants are more likely to be satisfied with their thermal environment when they are given a greater flexibility over their room temperature control, which illustrates that one of the options to improve thermal comfort level of occupants is to increase occupants' controllability over their thermal environment. For instance, Van Hoof (2008), Brager (2004), and Wyon (2000) all addressed the importance of individual control of temperature for thermal comfort and productivity. It can be argued that the low thermal comfort level recorded in low-rise MURBs is partially due to the low controllability in this type of dwelling.

However, both satisfactory rating and controllability are found to be either weakly or not associated with the respondents' overheating and overcooling frequency (Table 12). Respondents were asked to state how often they experience overheating and overcooling in winter and summer seasons respectively, with a scale from 1 to 4, with 1 being several times a day and 4 being never. Significant correlations were not determined for three of the four cases, which illustrates that the frequency in experiencing overheating or overcooling does not tend to have a significant impact on the respondent's satisfaction level and controllability over their room temperature. The reason for the poor correlations is probably due to the adaptive nature of the building occupants. People are not passive receivers as they would try to alter or adapt to the environment that they are subjected to. If a change occurs to the thermal environment and causing the occupants to be thermally uncomfortable, they will tend to restore their comfort by taking different actions (de Dear & Brager, 2001). Occupants can get adapted to frequent overheating or overcooling occasions if they are exposed to them long enough

Set-point temperatures during occupied hours for sedentary and sleeping periods for winter were asked to be stated in the survey. Kendall's tau-c test reveals there are no significant relationships between satisfaction rating and set-point temperatures (Table 12). This observation reveals that there exists a difference of desired temperature amongst building occupants and that higher set-point temperature during the winter does not necessarily improve comfort levels. However, there exists negative correlations between controllability and set-point temperature during occupied hours, both sleeping (p=0.00, γ = -0.203) and non-sleeping periods (p=0.04, γ = -0.119). The results show that respondents that indicated to have a relative high set-point temperature also perceive to have less control over their thermal environment. This indicates that providing dwellers with adequate personal control over temperature will lead to lower temperatures and therefore less energy use.

The usage of supplementary heating equipments is considered to be one of the occupants' adaptation actions when being subjected to an undesirable thermal environment. Respondents were asked whether they use supplementary heating equipments such as portable electric heater, fireplace or wood stove to satisfy the heating requirement of the space and 45.9% indicated they do. 55.2% of which used portable electric heater and 33.1% uses fireplace. The popular use of supplementary heating equipments indicates that relying on primary heating system alone might not be enough to satisfy occupants and as well, usage of supplementary heating equipment is common practices within the sample group.

However, results show that the usage of such equipment does not correlate with either the satisfaction rating or the controllability. It was found that out of the 74 respondents that are dissatisfied or very dissatisfied with their room temperature, almost half, or 48.6% of which already uses supplementary heating equipments, while out of the 28 respondents that are very satisfied with their room temperature, half of which uses supplementary heating equipments. This indicates that the usage of such equipments does not necessarily increase satisfaction rating (Fig. 31). A Mann-Whitney U test failed to show significance: $p > 0.05$ (two-tailed). Out of the 45.9% or 181 respondents that use supplementary heating equipments, 4.4% and 15.5% rates their satisfaction rating as dissatisfied and very dissatisfied, which is comparable to the sample's average. Similar case was observed with controllability. Statistical test shows that even supplementary heating equipments are used, thermal comfort levels are not significantly improved within the sample group. The use of supplementary heating equipment is considered to be temporary solutions and could not substantially improve satisfaction or increase controllability. Improvements need to be made directly with the primary heating system to mitigate system deficiency. The popular use of supplementary heating equipments signifies that the current primary heating system built today might not be able to satisfy the heating requirement of the space.

From the survey conducted by Scott et al. (2001), 90% of the respondents agree that a significant amount of energy is wasted by Canadians overheating or overcooling their homes. When asked if the respondents experienced overheating in the winter in their bedroom, 38.5% stated yes and 36.3% of that experienced overheating daily or more frequently and need to open their windows. Overheating can be caused by various reasons, such as temperature stratification through the house and the inability of single-zone systems to account for the different thermal load in different spaces. However, another reason for occupants opening their windows might be due to the insufficient ventilation provided by the HVAC equipment. Donnini et al. (1997) showed that the air velocity in mechanically ventilated offices in southern Quebec is quite low, at 0.08 m/s, which resulted in 53.5% of the occupants indicating a preference to have more air movement. Field studies or thermal simulation studies need to be conducted to evaluate whether the excessive use of windows during winter heating seasons is due to overheating or insufficient ventilation, or both. Similar question was asked if the respondents experienced overcooling in the summer in their bedroom and 33.0% of the respondents stated they experience overcooling in the summer, of which 50.4 % experienced overcooling daily or more frequently.

Table 12 - Satisfaction rating and controllability over thermal environment conditions

	Satisfaction Rating		Controllability	
	p	γ (Gamma)	*p*	γ (Gamma)
Overheating frequency	0.285	0.076	0.034	0.153
Overcooling frequency	0.436	0.061	0.819	0.017
Set point during occupied hours (excluding sleeping)	0.757	0.018	0.04	-0.119
Set point during sleeping hours	0.743	-0.018	0	-0.203
	p	Cramer's V	*p*	Cramer's V
Supplementary heating equipment	0.478	0.097	0.299	0.115

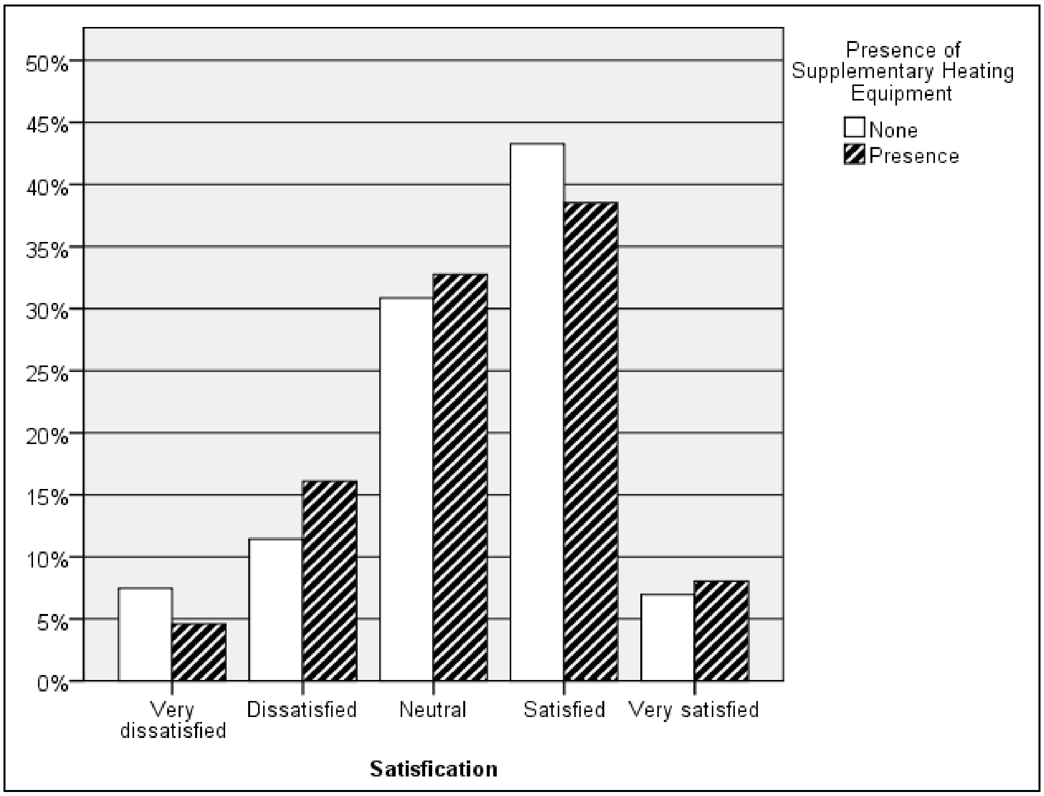

Figure 31 - Satisfaction with room temperature with and without supplementary heating equipments

4.3.4.2 System setup and operation

Within the sample group, there exist differences in the HVAC system arrangements. It is believed that certain factors within the HVAC system would influence occupants' thermal sensation. Three factors namely, number of programmable thermostats, age of heating system, and maintenance frequency of heating system were selected to be evaluated with occupant thermal sensations: satisfaction level, controllability, and overheating and overcooling frequencies.

Most people have a programmable thermostat for temperature control in their dwelling. Only 15.5% of the respondents stated they do not have a programmable thermostat at home. There are differences in the presence of programmable thermostats in the different house types (Fig. 32), for which 88.0% and 86.2% of the single-detached and double/row houses have programmable thermostats and only 55.1 % of the low-rise MURBs have this equipment.

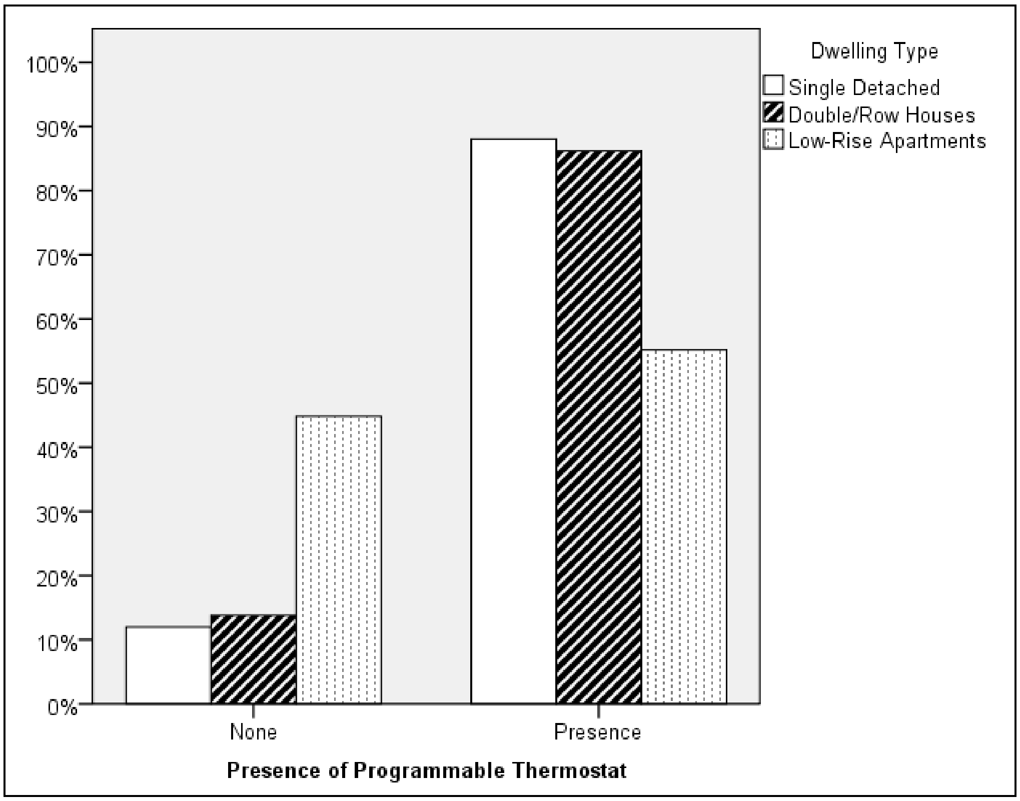

Figure 32 - Percentage of different types of houses equipped with programmable thermostat

The level of controllability is much lower in houses without programmable thermostats (Fig. 33). Thermostat number displayed a significant association with the respondents' controllability over their room temperature ($p = 0.005$, $\gamma = 0.26$). Respondents tend to have higher controllability over their room temperature if they have access to one or more programmable thermostats in the dwelling. However, the level of satisfaction rating does not seem to be affected by the presence of programmable thermostats (Fig. 34) and Kendall's tau-c test failed to show a significant association between thermostat number and satisfactory rating over room temperature. The reason for the poor correlation is believed to be due to the adaptive behaviour of occupants. Instead of relying on programmable thermostats to regulate their space temperature, they would actively alter or adapt to the environment by other actions. In supporting this point further, respondents were asked to select their predominant action when feel cold in winter and only 20.3% would configure the thermostat. 71.2% of the respondents would choose to dress up. The reason for programmable thermostats not being used frequently can be due to the inability of single-zone systems to supply adequate conditioned air to various spaces in the dwelling. Occupants might not believe that their thermal state can be restored by configuring the programmable thermostat not located in the room that is not conditioned properly.

On the other hand, the age of heating system is significantly correlated with satisfactory rating ($p = 0.016$, $\gamma = -0.144$), and controllability over room temperature ($p = 0.001$, $\gamma = -0.194$). Maintenance frequency is also found to be significantly correlated with satisfactory rating ($p = 0$, $\gamma = -0.254$) and controllability over room temperature ($p = 0.023$, $\gamma = -0.15$). Respondents that have older heating systems or do not maintain their system frequently tends to be less satisfied with their space temperature. The gamma coefficient between maintenance frequency and satisfaction rating is higher than that of age of heating system, suggesting satisfaction is more dependent on the maintenance frequency of the primary heating system.

Age of heating system is found to be significantly correlated with overheating frequency ($p = 0.005$, $\gamma = -0.193$) and overcooling frequency ($p = 0.035$, $\gamma = -0.148$). The negative correlations between age of heating system and overheating and overcooling frequency suggest that older systems tend to increase the occurrence of overheating and overcooling. As seen in table 13, only age of heating system is found to be significantly correlated with overheating and overcooling frequencies as Kendall's tau-c tests failed to show significant correlation between thermostat numbers or maintenance frequency with either overheating or overcooling frequencies. The reason for the high occurrences of overheating and overcooling in houses with older systems could be due to system deterioration and lack of maintenance of the primary heating and cooling systems, or the poor and less insulated building envelope systems in older houses. This observation deserves additional discussion and should be investigated in the future.

Chi-square test of significance and calculation of Cramer's V reveal that there are no significant correlations between thermostat numbers, age of heating system, or maintenance frequency with the use of supplementary heating equipments. Within the sample size, the usage of supplementary heating equipments is independent of the age of heating system, maintenance frequency, and programmable thermostat number.

Table 13 - System setup and operation with thermal environment conditions

	Programmable Thermostat Number		**Age of Heating System**		**Maintenance Frequency**	
	p	γ (Gamma)	*P*	γ (Gamma)	*p*	γ (Gamma)
Satisfactory rating	0.496	0.064	0.016	-0.144	0	-0.254
Controllability	0.005	0.26	0.001	-0.194	0.023	-0.15
Overheating frequency	0.223	0.123	0.005	-0.193	0.645	-0.033
Overcooling frequency	0.181	-0.145	0.035	-0.148	0.744	-0.025
	p	Cramer's V	*P*	Cramer's V	*p*	Cramer's V
Supplementary heating equipment	0.963	0.014	0.165	0.165	0.139	0.121

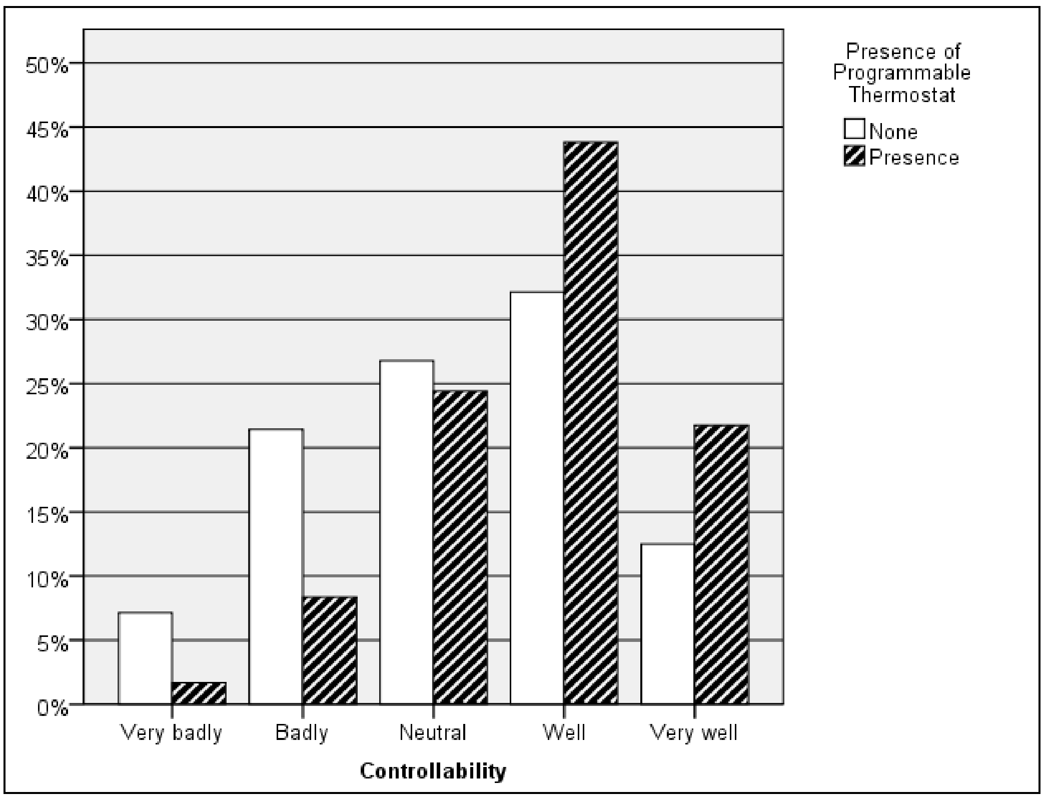

Figure 33 - Controllability with room temperature in dwellings with and without programmable thermostats

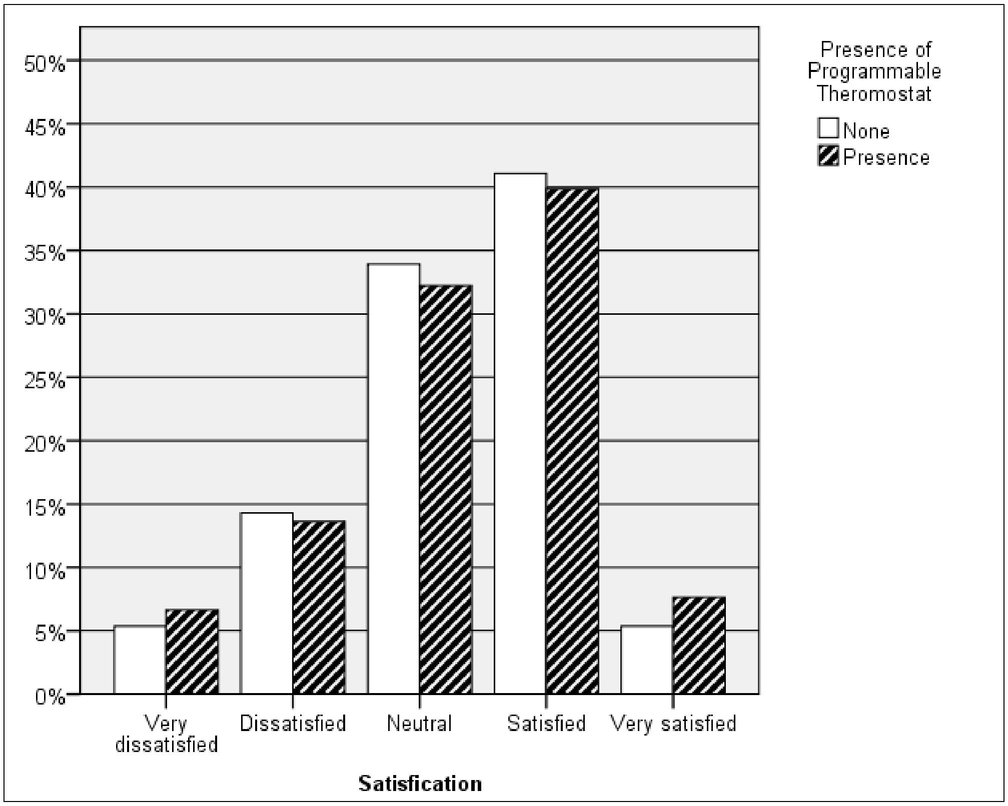

Figure 34 - Satisfaction rating in dwellings with and without programmable thermostats

4.3.4.3 Occupant behaviour

Current strategic programs employed by local government are concentrated in improving the energy efficiency of house through the design of building envelope and the selection of appliances (EnerQuality, 2009; NRCan, 2009; NRCan, 2010). While these are important aspects, current programs neglected to address the behavioural aspects of home energy use. Previously, standards like the ASHRAE 55 (ASHRAE, 2004) were derived from a reductionist model and views occupants as a passive recipients of thermal stimuli. This approach overlooks the thermal adaption actions from occupants, and often leads to oversized heating and cooling systems. It also assumes universality and ignored cultural, climatic, social, and contextual variations, which had been critically questioned against. The attitude toward the use of heating and cooling equipments and windows play a significant role in energy consumption in residential building. For instance, Bahaj and James (2007) found that electricity consumption in nine identical social housing units varied by as much as

600% in some periods of the year. Earlier, Seligman et al. (1977) investigated the energy consumption in 28 identical townhouses and it varied by as much as 200%. More recently the adaptive approach to thermal comfort has received much more attention as it tries to establish the interaction between people and their thermal environment (deDear & Brager, 2001). Occupants adapt and acclimate to their surroundings by adopting different behaviours. There is a limited amount of research literature on survey studies in residential houses in Canada.

Previously, Scott et al. (2001) performed an extensive survey study examining energy efficiency behaviours in Waterloo, Ontario. He categorized behaviours to three groups, willingness to invest on energy-efficient equipments, and behaviours related to energy management and reducing consumption and investigated their associated significant predictor variables, using a stepwise multiple regression analysis. The study conducted by Scott et al. (2001) has some shortcomings. Specifically, the demographic profile of the survey respondents might not be representative to the provincial average. The average age of the respondent was 47.3, compared to 39 for the province as a whole (StatsCan, 2006); more importantly, the ownership proportion, educational level and household income was relatively higher than the provincial average, 94% of the respondents owned the dwelling that reside in, compared to 71.1% for the province (StatsCan, 2006); and as well 66% had a university degree, compared to 22.9% for the province (StatsCan, 2006). Previous studies have found positive correlations between ownership and energy technology investment (Andersen et al., 2009) and education level and environmentally responsible actions (Kasapoglu, 2002). With a more provincially representative sample, this study aims to identify behavioural actions that specifically relates to the control of the thermal environment.

As mentioned briefly in the previous section, only 20.3% of the respondents would choose to configure their thermostats when feel cold in winter. 71.2%, 4.1 %, 3.1 % and 1.3% would choose to put more clothes on, use supplementary heating equipments, tolerate, and get in contact with person in charge respectively. Karjalainen (2008) did a similar study in Finnish homes and only 52% of the respondents chose to put more clothes on, and 22% and 16% of which would choose to configure their thermostats and use supplementary heating. For the past decades, Europeans have generally been perceived to have adopted a more responsible energy consumption pattern than North Americans. Although this appears to be the norm, survey results shows the contrary when a larger portion of the respondents in this survey would rather put more clothes on than configuring their thermostats or use supplementary heating equipments when feeling cold in winter. The discrepancy between the studies may be due to social or cultural differences, and not necessarily due to the dissimilarity of energy conservation behaviours between the two populations. This topic would require further examination and will be reported in further publications.

Setting back the temperature set-point when the dwelling is unoccupied is considered good practices but only 40.9% of the respondents do so during the day when away from home. Respondents tend to setback their temperature during the day if their space is equipped with programmable thermostats, 41.6% of the respondents that have at least one programmable thermostat would setback their temperature during the day, while only 37.5% of those who don't have programmable thermostat would setback their temperature. However, there was no significant association between the presence of programmable thermostats and the tendency to setback room temperature during the day as Chi-square test failed to show significance: $p > 0.05$. This shows that the presence of programmable thermostats does not encourage or increase the practice of setting temperature back during unoccupied hours to conserve energy. Further communication with the occupants revealed that this because they did not have sufficient knowledge on the systems. Relying on the voluntary actions of occupants to use the programmable thermostats in the way they are planned to be used is problematic. Education program should be created with support from relevant authorities and utility suppliers. Similarly, during the night, 52.0% of the respondents that have at least one programmable thermostat would setback their temperature, while 53.6% of those who don't have programmable thermostat would setback their temperature. To some extent, this result corresponds to Scott et al. (2001), where he found in 90% of the time, 56% of the respondents would adjust thermostats when no one is at home or in evening.

Opening windows while the heating or cooling system is operating is considered to be bad practices for energy conservation. However, the excessive occurrence of this behaviour suggests that either the occupants are not aware of the impact it has on energy consumptions, or the current HVAC system could not provide them with the necessary IEQ and therefore left them with no options but to conduct such undesirable behaviour. Opening window in promoting circulation in overheating or overcooling occasions can be considered as an adaptive behaviour. When occupants feel that they are subjected to a thermally unacceptable environment, they would sort ways to restore their thermal satisfaction. Current system arrangement does not provide a great deal of flexibility in allowing occupants to control their thermal environment, particularly due to the single-zone system where conditioned air would only be supplied to spaces when temperature at the thermal sensor in the dwelling is not met. The thermal sensor is usually placed at the entrance area of the dwelling and therefore could not account for the temperature variations between the different spaces in the dwelling. Existing technologies could perhaps help alleviate the discomfort experienced by occupants at minimal added operating costs. For instance, Heat Recovery Ventilators (HRV) can help provide sufficient ventilation to a space whilst recovering the valuable energy by transferring heat from the exhaust air stream to the incoming air stream. Most low-rise dwellings built to date are not required to install HRVs and due to the first cost involved in installing this equipment, low-rise dwellings are not commonly equipped with HRVs. The use of HRVs should be encouraged due to its potential to conserve energy, improve thermal comfort, and reduce life-cycle cost of the HVAC system by lowering energy costs.

Respondents were also asked to state their weekday and weekend set-point temperature during winter and are as illustrated in Fig. 35. The average winter set-point temperature is 19.7^{o}C. There exist differences between weekdays and weekends as weekend's set-point temperature during the day is almost 1^{o}C higher than that of weekdays. The set-point temperatures are lower than expected as it lies in the lower range of the recommended winter operative temperature as laid out in ASHRAE 55-2004 (ASHRAE, 2004). This suggests that people residing in Ontario might have adapted to a lower comfort temperature. Field studies needs to be conducted to mathematically determine the neutral operative temperature of Ontario dwellings so as to compare with other published results in Canada and other parts of the world such as those summarized in Donnini et al. (1997), Cena & de Dear (1999), and Wang (2006).

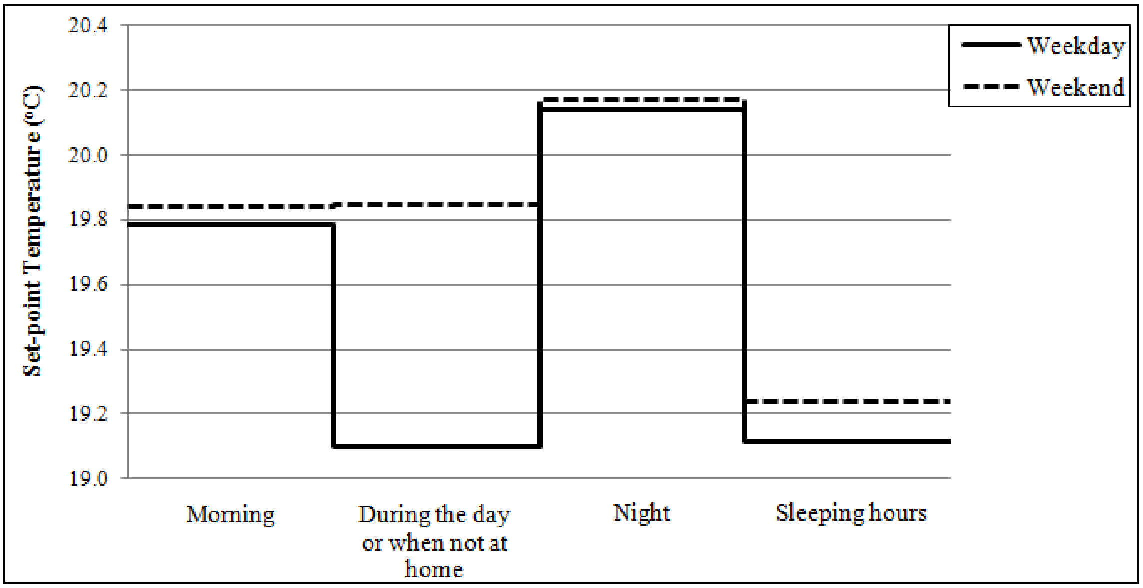

Figure 35 - Set-point temperature in winter throughout the day

4.3.5 Conclusions on survey results

The analyses of the survey results offer many insights into the systems built today in low-rise residential houses and on the basis of the survey analyses, the following recommendations are made:

- Inadequate level of controllability over room temperature is perceived as the most serious problem as evidenced by the excessive occurrences of overheating and overcooling, and the common usage of supplementary heating equipments. Observations from the survey results helped identify the deficiencies of the heating equipments built today and suggest improvements should be made to increase the controllability of current systems. It was found that almost 20% of the respondents expressed dissatisfaction with room temperature, which barely aligns with the 80% acceptability target as laid out in common thermal standards. Corresponding to previous literatures, the relationship between satisfaction and controllability are found to be significant and the correlation strength is determined to be moderate. The number of thermostats and controllability is also significantly correlated. This suggests that the controllability over room temperature could be improved by greater availability of thermostats. Increasing the controllability of occupants, specifically granting occupants a higher degree of personal control is a promising way in improving thermal comfort, as illustrated in the present and previous studies. Thermal simulations will be conducted in help identifying the deficiency of single-zone systems and evaluate potential retrofit alternatives.

- Certain system setup and operational factors were found to be correlated with occupants' thermal sensations. The age of the primary heating equipments and their maintenance frequency is significantly correlated with thermal comfort levels and controllability. Thermal comfort can potentially be increased when primary heating systems are maintained more frequently.
- On top of deficiencies in current system arrangements, only 41% and 52% of the respondents set temperature back during the day when the dwelling is unoccupied and during the night respectively. The presence of programmable thermostats does not encourage respondents in adjusting set-point temperature as statistical test failed to show significance. This suggests that relying on the occupants' voluntary action in configuring the thermostat is problematic and therefore calls for further actions, such as introducing educational programs or incorporating more advanced technologies. The potential of existing equipment or technology in reducing energy consumption is hindered when they are not used in the way they were planned. Educating occupants in properly operating equipments already installed in their dwellings provide a big potential in reducing energy consumption without any capital investments and therefore should be considered and pursued.

4.4 The simulation model

From the survey results, there is an opportunity to improve thermal comfort by increasing occupants' controllability over their thermal environment. Thermal simulations with EnergyPlus were taken place to first, evaluate the problems with single-zone systems commonly built today, and subsequently, investigate the potential retrofit alternative. A typical house was selected and was used as the subject of thermal simulation. The selected building (Figure 36) is an existing single-detached house located in Toronto, Ontario. The building consists of three levels with two levels above grade. The total floor area is approximately 290 m^2 (3120 ft^2).

Figure 36 - Selected single-detached house for thermal simulation

4.4.1 Simulation model parameters

A building model was established in DesignBuilder (Fig. 37-39). Referring to the design drawings provided by the occupant, the facades on all four sides are constructed with a 100mm brick layer on the exterior face, followed by layers of 25.4mm air cavity, 95mm expanded polystyrene insulation (EPS), plywood, and gypsum board on the inside. The below-grade wall consists of a layer of 200mm concrete, followed by layers of 25mm EPS insulation, plywood, and gypsum board on the inside. The roof is topped with a layer of roofing clay tile and is insulated with a layer of 145 mm EPS insulation. The windows are clear, double glazed units framed with polyvinylchloride (PVC). The properties of the various materials used in the model are summarized in Table 14. The thermal resistance value of the envelope components are as listed in Table 15.

Table 14 - Thermal properties of materials

	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)
Brick	1700	800	0.84
Concrete	1400	1000	0.51
Clay tile roofing	2000	800	1
Gypsum wall board	900	1000	0.25
Expanded Polystrene insulation	15	1400	0.04
Plywood	560	2500	0.15

Table 15 - Thermal resistance of base case building envelope

	U (W/m^2K)	Thermal Resistance RSI (m^2K/W)	R (Imperial)
Above-Grade Wall	0.332	3	17.0
Below-Grade Wall	0.707	1.4	7.9
Roof	0.185	5.4	30.7
Windows	2.71	0.37	2.1

ASHRAE Handbook of Fundamentals (2005) published typical values for the different category of air-tightness level in low-rise houses and is as summarized in Table 16 in normalized leakage rate (NLR) (cfm/ft^2 and $L/s{\bullet}m^2$ at 75 Pa). For the purpose of this study, the infiltration of the house is assumed to be at the average level, at 0.013 $L/s{\bullet}m^2_{\text{envelope area}}$ (Table 16). Using the conversion formulas from Chapter 27 of the 2005 ASHRAE Handbook – Fundamentals, the infiltration rate is 1 ACH at normal operating condition.

Table 16 - Air-tightness values as per ASHRAE handbooks – fundamental

	NLR_{75} ($cfm/ft^2_{\text{envelope area}}$)	NLR_{75} ($L/s{\bullet}m^2_{\text{envelope area}}$)
Leaky	0.6	3.05
Average	0.3	1.52
Tight	0.1	0.51

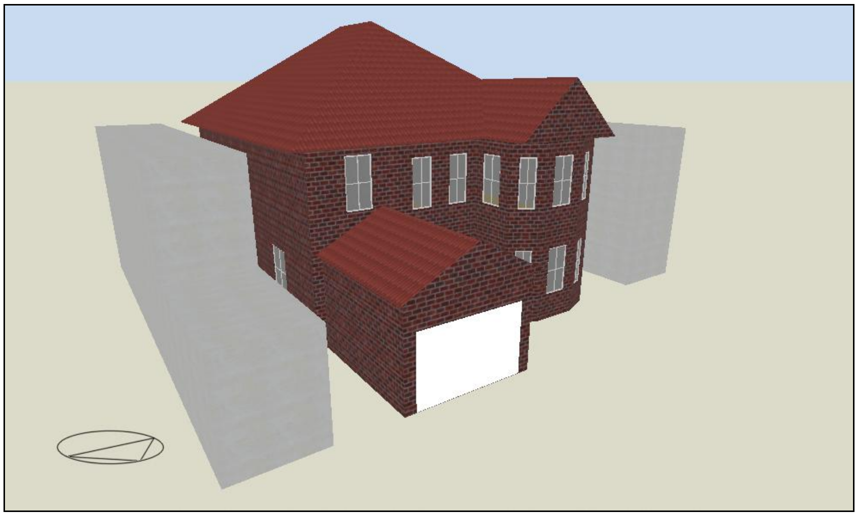

Figure 37 - Geometric representation of the building

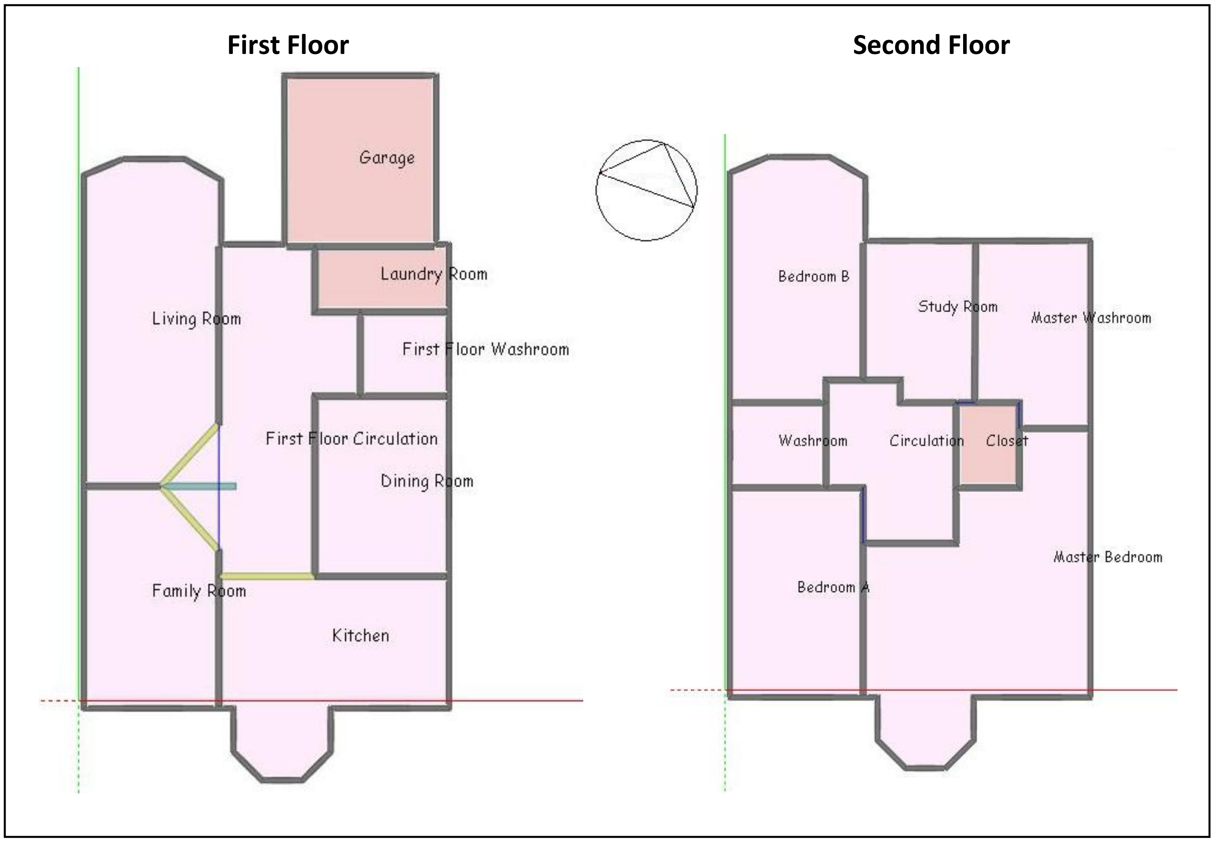

Figure 38 - Floor plan of the subjected building

The house is conditioned by a central heating system with a single-stage gas furnace with 84% efficiency. The living room area acts as a control zone as set out by the thermostatic control zone for unitary system with a programmable thermostat placed at the zone. The heating set-point was 19°C and the occupants do not set temperature back. The configuration of the HVAC system employed in the model is as illustrated in Figure 39.The building is occupied by two adults and two children. The time occupants spent in each of the spaces (Table 17) were also inquired to account for internal heat gains in the model.

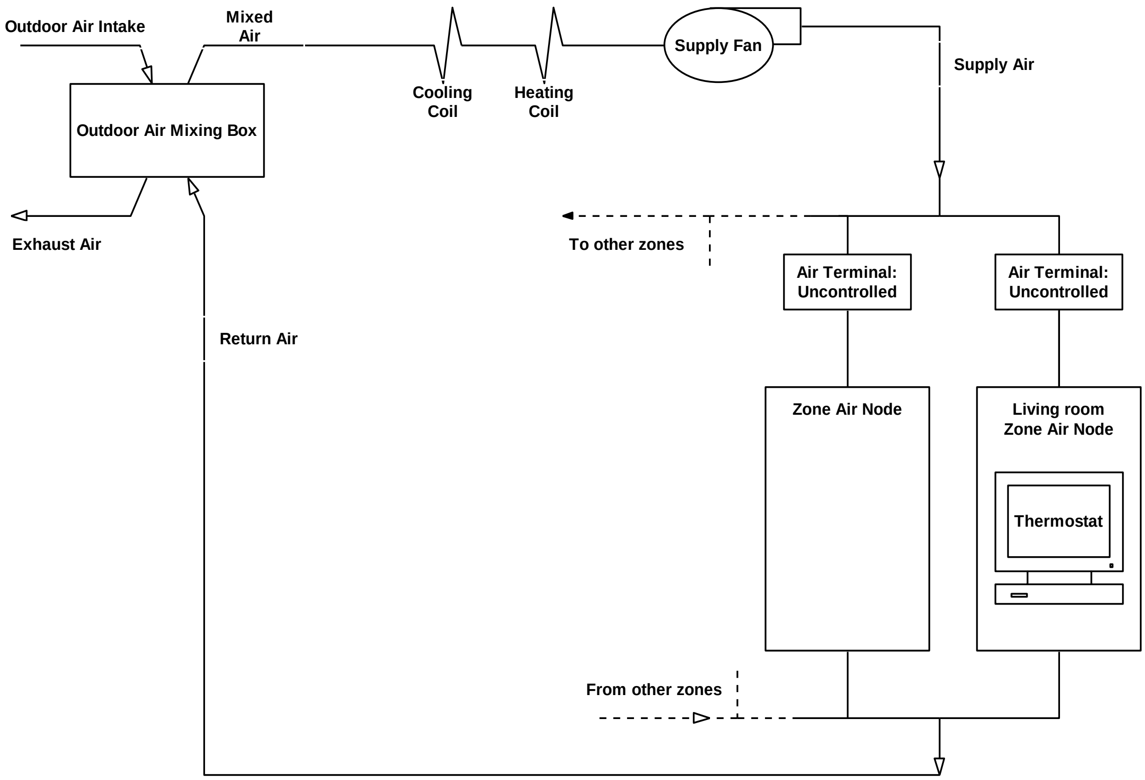

Figure 39 - HVAC setup for Basecase

Table 17 - Occupancy Schedule

	Weekdays	Weekends
Dining Room	07:00-09:00; 18:00-20:00	09:00-11:00; 13:00-14:00; 18:00-21:00
Kitchen	07:00-09:00; 17:00-19:00	09:00-11:00; 13:00-14:00; 17:00-20:00
Family Room	18:00-23:00	10:00-24:00
Living Room	18:00-23:00	10:00-24:00
Master Bedroom	24:00-09:00; 21:00-24:00	24:00-11:00; 22:00-24:00
Bedroom A	24:00-09:00; 21:00-24:00	24:00-11:00; 22:00-24:00
Washroom	07:00-09:00; 22:00-23:00	09:00-10:00; 15:00-16:00; 21:00-22:00
Bedroom B	24:00-09:00; 21:00-24:00	24:00-11:00; 22:00-24:00
Study Room	21:00-23:00	-
Master Washroom	07:00-09:00; 22:00-23:00	09:00-10:00; 15:00-16:00; 21:00-22:00

4.4.2 Simulation model calibration

When evaluating existing building's performance with thermal simulation programs, model calibration is required so that the observed energy performance matches the predicted energy performance as closely as possible. Model calibration would result in a model that is more representative to the thermal and energy behaviour of the subjected building. There are three standards that governs the bounds within which a simulation model is considered calibrated, namely, ASHRAE Guideline 14-2002 (ASHRAE, 2002), International Performance Measurement and Verification Protocol (IPMVP) (Efficiency Valuation Organisation 2007), and the Federal Energy Management Program (FEMP) Monitoring and Verification Guide (US DOE 2008b). For the purpose of this study, the bounds as laid out in ASHRAE Guideline 14-2002 will be employed. In section 6.3.3.4.2.2, the guideline suggested that models are considered calibrated if they produce Normalized Mean Bias Error (NMBE) (Eq. 19) within ±10% and Coefficient of Variation of Root Mean Squared Error (CV-RMSE) (Eq20) within ±30% when using hourly data, or 5% to 15% with monthly data. NMBE and CV-RMSE are two major measures to evaluate the goodness of fit of the model. The measurements are defined below:

$$NMBE = \left[\frac{\sum_{i=0}^{n}(y_{Mi} - y_{Oi})}{n-p}\right]\frac{1}{\bar{y}_O} X\ 100\% \qquad (19)$$

$$CV - RMSE = \sqrt{\left[\frac{\sum_{i=0}^{n}(y_{Mi} - y_{Oi})^2}{n-p}\right]}\frac{1}{\bar{y}_O} X\ 100\% \qquad (20)$$

Where,

y_{Oi} = Observed energy consumption for each interval

y_{Mi} = Model simulated energy consumption for each interval

$\bar{y}_O$ = Mean observed energy consumption

n = Number of observations

p = Number of model parameters

The above documents primarily focus on protocols in measuring, verifying, and characterizing the existing building performance for Measurement and Verification (M&V) projects. Although they recommend the use of calibrated thermal simulation models to evaluate savings from proposed energy conservation measures, these documents do not provide a standard methodology to calibrate a simulation model. There are several methodologies that are commonly used and are described briefly in published research papers (Pan et al. 2007; Pedrini et al. 2002; Westphal & Lambers, 2005; Raftery et al., 2009). Reddy (2005) conducted a comprehensive literature review on calibration of thermal simulation models and categorized calibration methods into four groups: calibration based on manual, iterative, and pragmatic intervention, calibration based on a suite of informative graphical comparative displays, calibration based on special tests and analytical procedures, and analytical/mathematical methods of calibration. For this study, the simulation model was calibrated using the manual iterative approach.

The power output of the central furnace was recorded for a period of three months, from January to March, 2008. The temperature and humidity were also calibrated. The indoor air temperature and humidity were monitored over the period of 90 days and at intervals of 10 min. Four HOBO data loggers were used for the measurement of indoor temperature and humidity in four different rooms, namely kitchen, family room, master bedroom, and study room.

By comparing the observed measurements to the simulation results using the International Weather for Energy Calculations (IWEC) climatic data for the nearest weather station, Toronto Buttonville Airport for the year of 2008, the simulation model was refined over a number of iterations to represent the actual building as closely as possible. The energy model was first created using the as-built drawings as well as operational parameters mentioned in the previous section. Subsequently, an in-depth field survey was conducted with the occupants and a number of operational parameters were manipulated, including, maximum flow rate of air terminal units, part load of central furnace, lighting power densities, and infiltration rates.

The calibrated model represents the subjected building fairly well. Fig. 40 illustrates the recorded heating energy consumption for each day from January 1st to March 31st, 2008 and the corresponding heating energy consumption predicted by the simulated model. Using Eq. 19 and 20, a CV-RMSE and NMBE of 22.16% and 2.22% were recorded for the daily results. Table 18 represents the recorded and simulated monthly heating energy consumption from January to March, 2008. Using Eq. 19 and 20, a CV-RMSE and NMBE of 5.71% and 1.86% were recorded and the values are within the bounds (CV-RMSE<15% and NMBE <5%) provided by ASHRAE Guideline 14-2002.

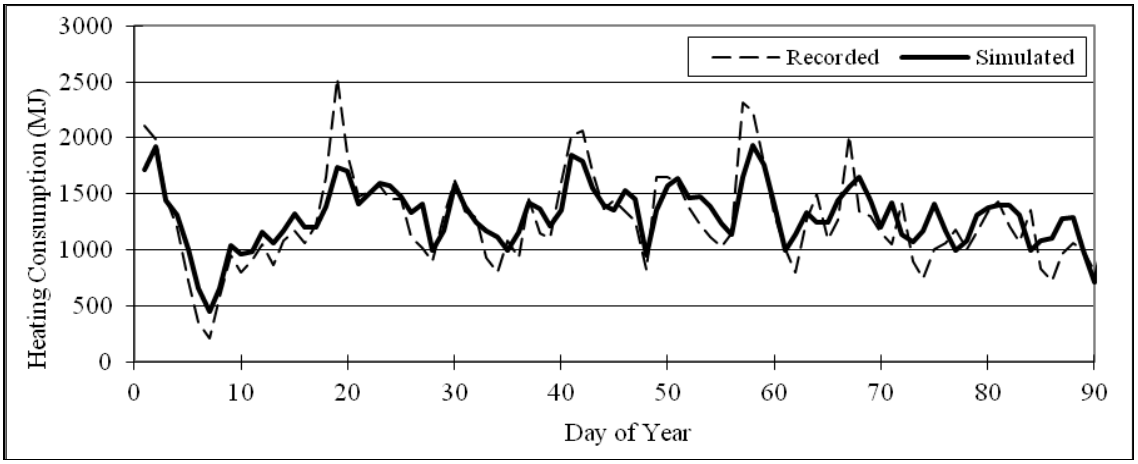

Figure 40 – Recorded and simulated daily heating energy consumption

Table 18 - Recorded and simulated monthly heating energy consumption (MJ)

	Recorded	Simulated
January	38492	39559
February	40845	39561
March	35434	38368

The temperature distribution in the Basecase model also corresponds to the recorded data fairly well (Fig. 41-44). Figures 41-44 compared the temperature simulated and recorded in the four rooms for the week of January 21st, 2008. Temperature measurement from the HOBO loggers indicated that, except for the dining room, the 19°C set-point temperature was not maintained. Using Eq. 19 and 20, CV-RMSEs and NMBEs were calculated for the hourly data and are as summarized in Table 19. The discrepancy between the recorded and simulated temperatures can be reasoned to temperature stratifications and inability for the simulation model to take occupant's adaptive behaviours into account. The temperature is recorded at floor level for the four spaces and the simulated temperature is the average indoor temperature predicted by the simulation model. With that acknowledged, the results generated by the simulation model are within reasonable range with the recorded data. Table 19 illustrates the simulated temperature profiles are within 5% of the measured value, which is significant from a statistical point of view.

Table 19 - Discrepancy between recorded and simulated hourly indoor air temperature in various rooms (^oC)

	CV-RMSE	RMSE
Dining Room	3.01%	0.59
Family Room	2.50%	0.42
Master Bedroom	4.99%	0.89
Study Room	4.02%	0.71

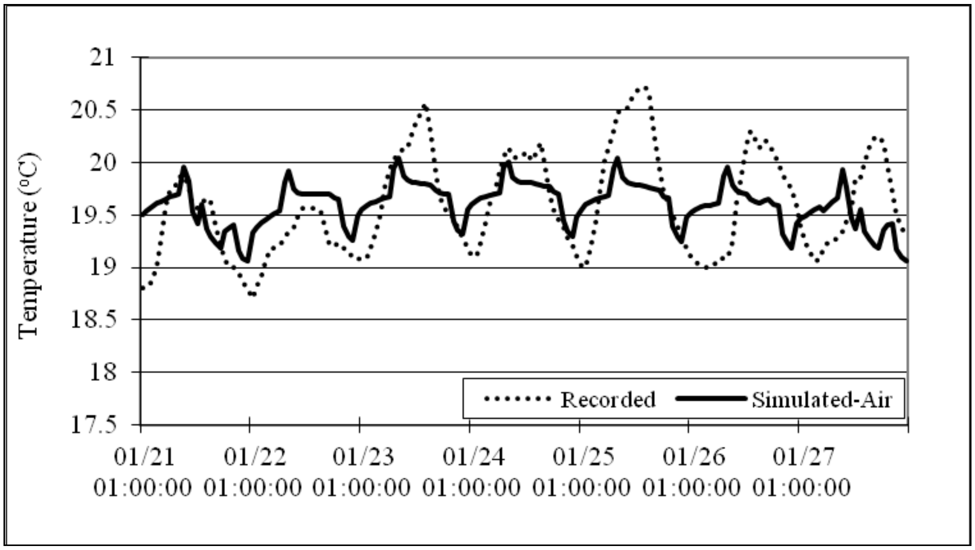

Figure 41 - Dining room's recorded temperature and simulated temperature using calibrated model

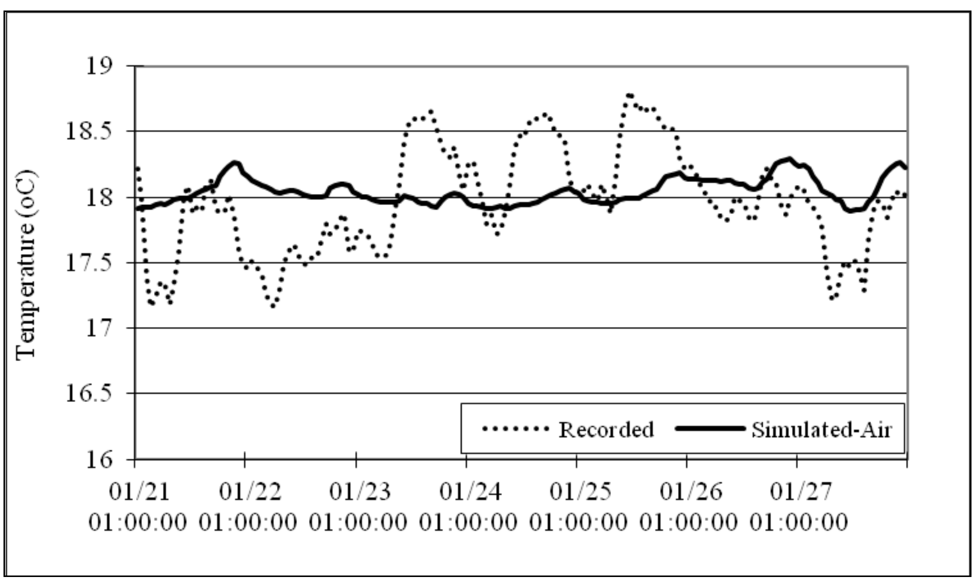

Figure 42 - Family room's recorded temperature and simulated temperature using calibrated model

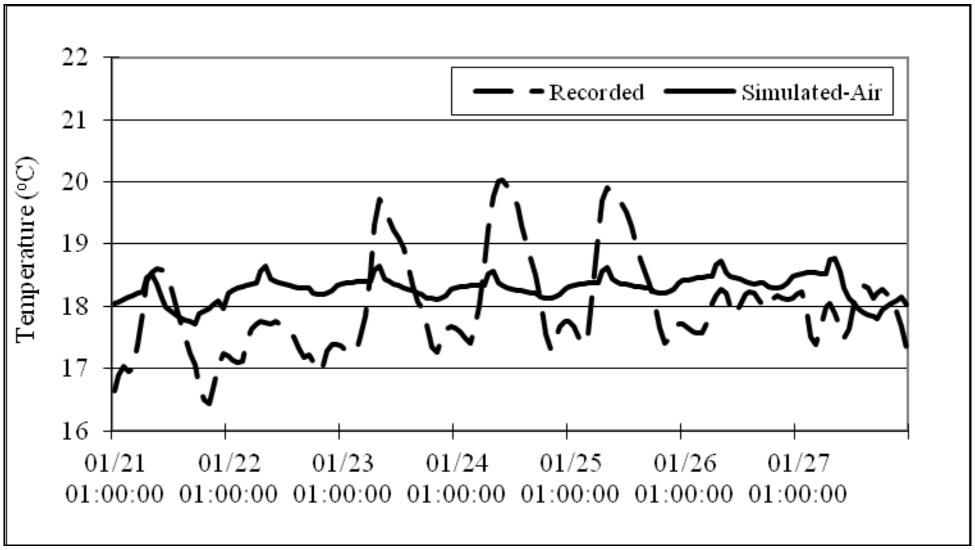

Figure 43 - Master bedroom's recorded temperature and simulated temperature using calibrated model

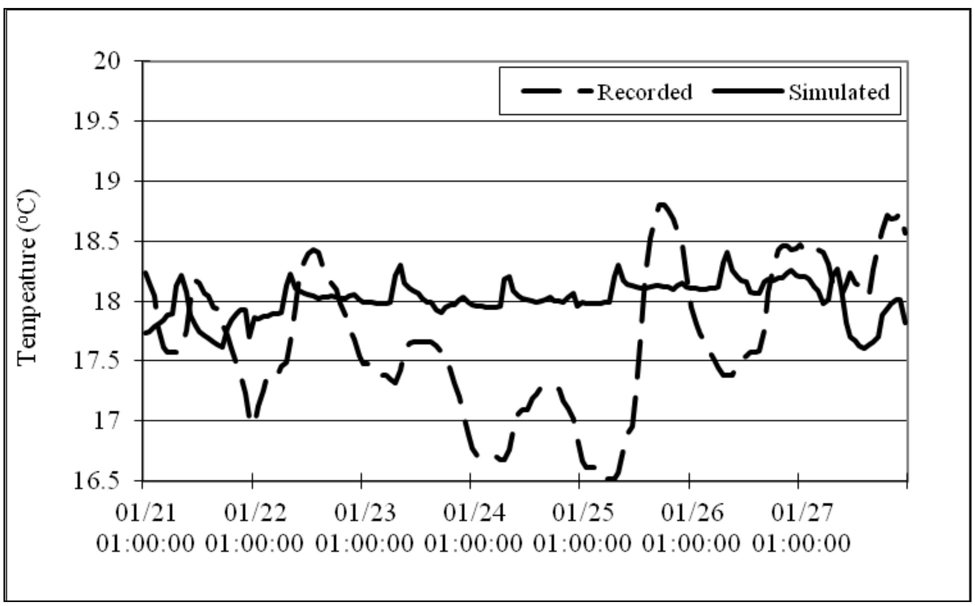

Figure 44 – Study room's recorded temperature and simulated temperature using calibrated model

Fig. 45-48 compared the recorded and simulated relative humidity in the four rooms installed with data loggers. It shows that the humidity level is within reasonable range in the recorded data but is significantly lower in the simulated results. The humidity level recorded corresponds to the occupancy schedule very well. The humidity level in the dining and family room peaks late in the afternoon every day (Fig. 45-46)Domestic activities such as cooking and washing dishes are usually conducted during that period of time in the kitchen, for which is located next to the dining and family rooms. On the other hand, the humidity level in the master bedroom gradually increases from late night to early morning every day (Fig. 47). This corresponds to the sleeping schedule of the occupants. The occupant indicated that the study room is only occasionally occupied throughout the week and this corresponds to the humidity level recorded (Fig. 48). The thermal simulation however, did not take moisture sources such as domestic activities and occupant's metabolic process such as evaporation and breathing, into account. As a result, the humidity level predicted by the thermal simulation model does not correspond well to the recorded data. It is important to note that humidity levels are not accounted for in the model when analyzing simulation results.

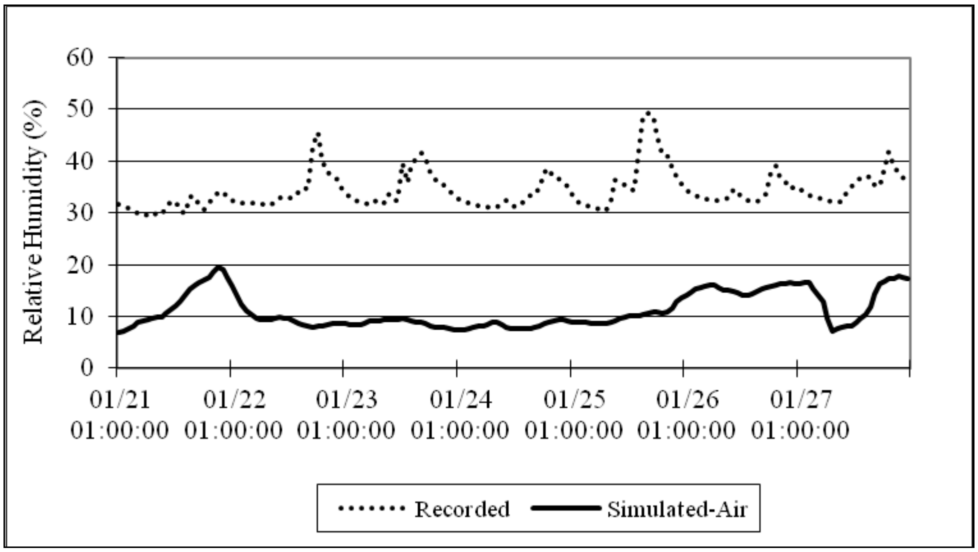

Figure 45 - Dining room's recorded RH and simulated RH using calibrated model

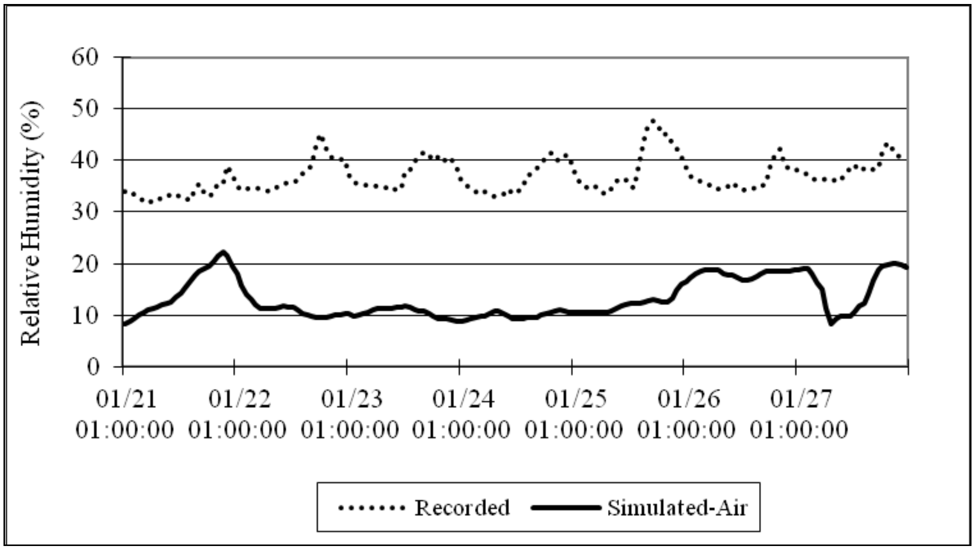

Figure 46 - Family room's recorded RH and simulated RH using calibrated model

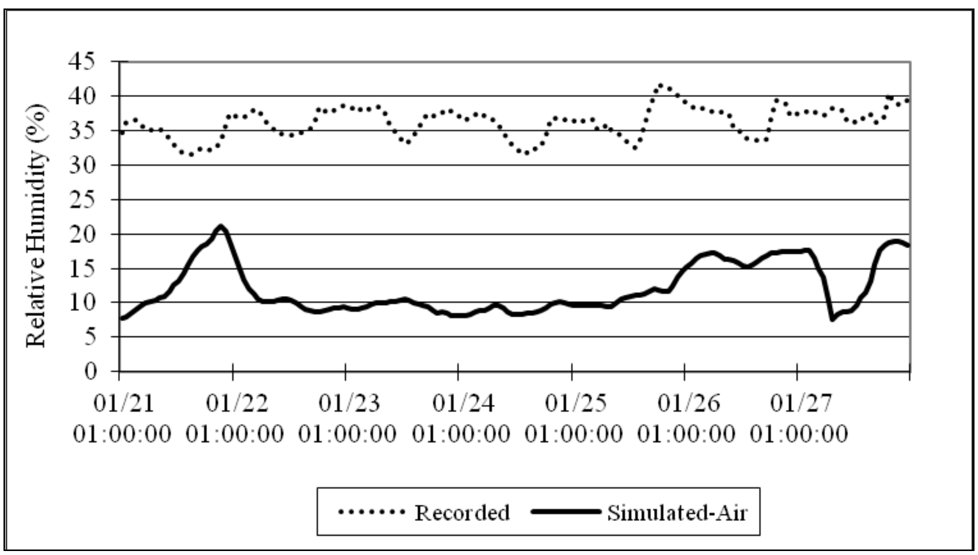

Figure 47 - Master bedroom's recorded RH and simulated RH using calibrated model

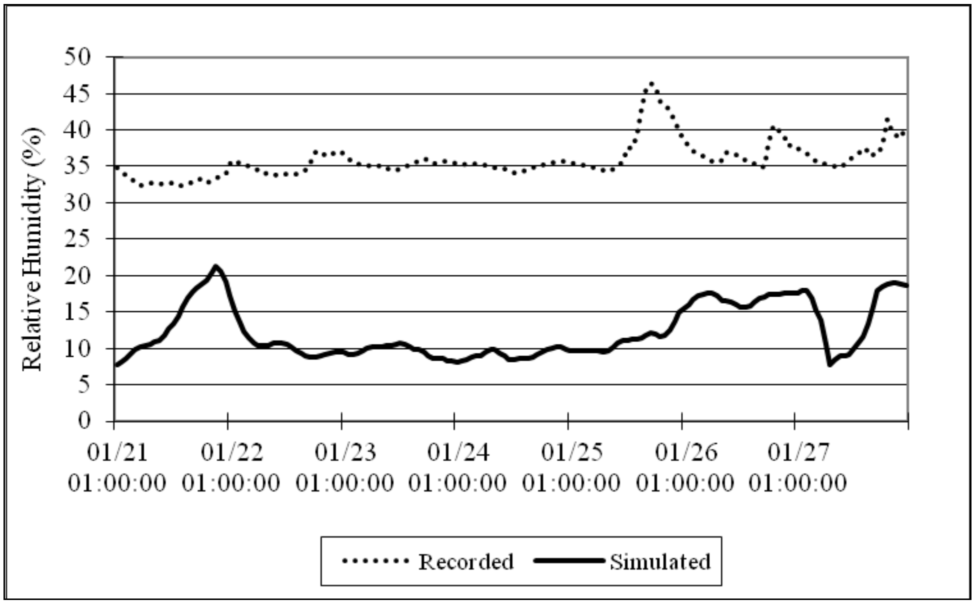

Figure 48 - Study room's recorded RH and simulated RH using calibrated model

4.4.2 Multi-zone system model parameters

With almost 20% of the respondents from the survey indicated thermal dissatisfactions and the high occurrence rate of overheating and overcooling, the survey results call for modifications to the current single-zone forced-air system to improve on thermal comfort levels.

As mentioned previously, the heating and cooling loads of houses built today are generally overestimated, which is partly due to the common practice of utilizing single-zone constant air volume (CAV) HVAC systems for conditioning the entire house (Refern et al., 2007). This typically results in inefficient heating or cooling due to the differences in thermal load in different spaces throughout the house (Wang & Jin, 1999), and in turn reduces the thermal comfort of occupants as well as wasting energy used for over-conditioning these spaces (Ardehali & Smith, 1996).

As an alternative, single-zone system can be converted into a multi-zone, variable air volume (VAV) system by adding modulating dampers, temperature sensors, and a central microprocessor, or another approach is to use variable capacity furnace matched with a variable speed fan (CMHC, 1986). CMHC (1986) conducted a comprehensive investigation of ways in optimizing residential forced-air HVAC systems and ruled out zoning to be one of the major recommendations, stating, "…zoning is not required in new construction since temperature homogeneity is readily achieved. With a reasonable well insulated, tight envelope, zoning has not been shown to produce energy savings...." However, there are a few shortcomings of CMHC's study. Firstly, the study conducted mainly focused on energy consumptions and disregarded thermal comfort requirements. Secondly, it was based on energy costs in the 1980s. And lastly, was based on the assumptions that air sealing construction techniques and insulation requirement will be improved and increased significantly over the years; their study expected that new residential construction will soon approach R2000 insulation and air-tightness levels.

Nonetheless, with the changing perception of the importance of thermal comfort in conditioned spaces, escalating energy prices, and relatively minor changes to the residential construction practises, it is worth revisiting the potential benefits multi-zone system can bring to existing houses. Multi-zone system can efficiently meet the heating and cooling requirements during peak and partial load conditions while maintaining thermal comfort requirements for individual rooms (Aktacir et al., 2005; Sekhar & Chung, 1997). These systems may provide a platform to effectively condition various zones within a house while significantly reducing the overall energy consumption.

Utilizing the same central heating system with the single-stage gas furnace, the house is divided into multiple control-zones with each zone having its own thermostat (Fig. 49). Air flow to each zone is controlled by a mechanical damper in the duct to regulate the zone's temperature. The minimum air flow fraction for the terminal units were set to be 0.35. Each terminal unit is equipped with reheat coils. During heating operation, as the heating load increases, the terminal unit starts at minimum air flow with reheat coils start with minimum hot water flow. The hot water flow is increased until it reaches maximum flow, then the damper starts to open to meet the load. A copy of the simulation file is included in the CD-Rom provided alongside with Appendix B of this thesis. A multi-zone system offers additional control and comfort to the occupant and is believed to be able to reduce heating load. For the purpose of this study, the house is subdivided into ten zones with each zone characterized with a distinctive occupancy schedule (living room, kitchen, bathroom, bedroom, etc.). Simulations are conducted with set-point and setback temperatures at 23^{o}C and 21^{o}C, respectively.

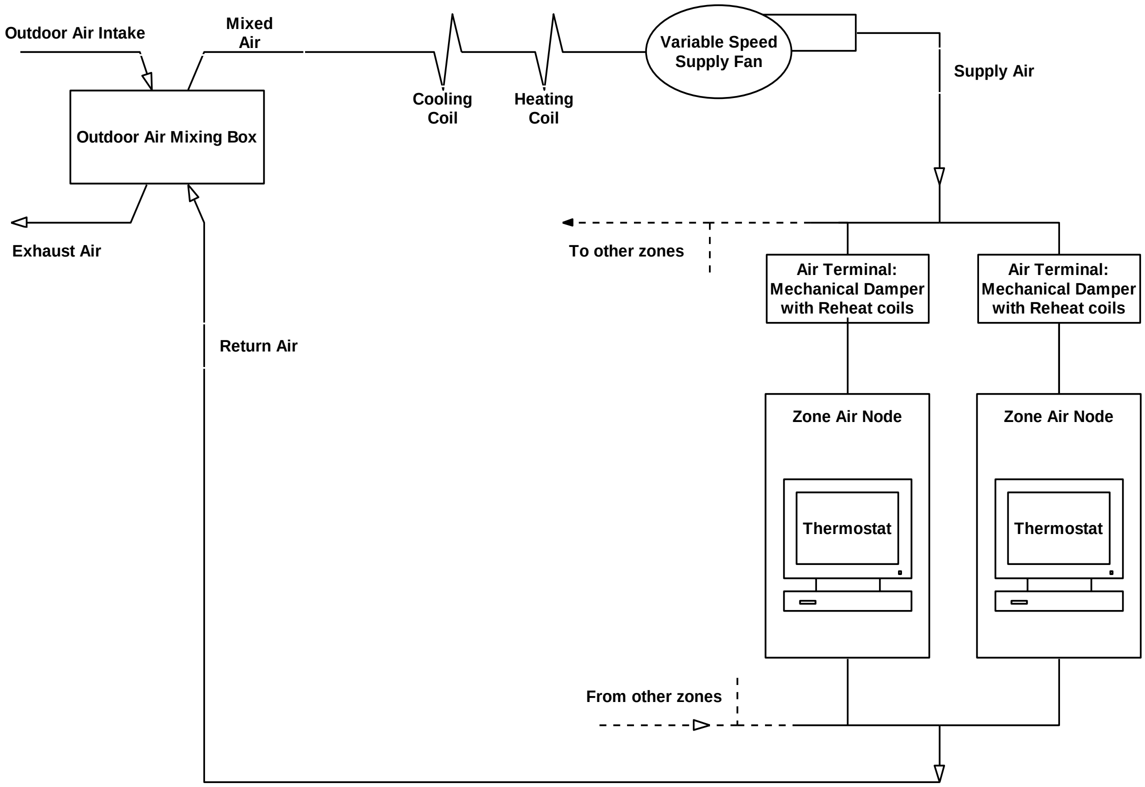

Figure 49 - Multi-zone configuration

4.5 Performance evaluation indices

To evaluate the impact on indoor environmental conditions by installing a multi-zone system as oppose to a single-zone system, two indices are used, namely the Fanger's Predicted Mean Vote (PMV), and hours not within ± 2^{o}C of set-point.

Many researchers have been exploring ways to predict the thermal sensation of people in their environment based on the personal, environmental and physiological variables that influence thermal comfort. Thermal comfort, as defined by ASHRAE 55-2004 is "that condition of mind which expresses satisfaction with the thermal environment". Two of the most notable models used in predicting thermal comfort levels were developed by P.O. Fanger (the Fanger PMV Model) and the J. B. Pierce Foundation (the Pierce Two-Node Model).

The Fanger PMV Model was developed from laboratory and climate chamber studies and is based on thermoregulation and heat balance theories (Fanger, 1972). According to the these theories, the human body employs physiological processes, which includes sweating, shivering, and regulating blood flow to the skin to maintain a balance between the heat produced by metabolism and the heat lost from the body. Maintaining this heat balance is the first condition for achieving a neutral thermal sensation. Fanger determined that the only physiological processes influencing this heat balance in this context were sweat rate and mean skin temperature, and that these processes were a function of metabolic rate. Fanger then measured sweat rate and skin temperature on people who indicated they have achieved neutral thermal sensation. In these studies, participants were dressed in standardised clothing and completed standardised activities, while exposed to different thermal environments. Using the measured data, he then established a relationship between skin temperature and sweat secretion with metabolic rate using regression analysis with the measured data. Later, Fanger expanded on the relationship between physiological processes, thermal environment, and neutral thermal sensation by conducting laboratory and climate chamber studies with 1396 participants. The resulting equation combines four physical variables, namely air temperature, air velocity, mean radiant temperature, and relative humidity, and two personal variables, namely clothing insulation and metabolic rate into an index that can be used in predicting thermal comfort. Fanger's proposition was that, except for the four physical variables and two personal variables, other factors have no significant effects on the state of thermal comfort. This equation related thermal conditions to the seven-point ASHRAE thermal sensation scale (Table 20) and become known as the PMV index. The quality of the thermal environment may be expressed by the predicted percentage dissatisfied (PPD) index, which is related to the PMV value. For PMV = 0, PPD is equal to 5%, that is 5% of the occupants are dissatisfied with the thermal environment. A PMV = ±0.5 will correspond to 10% being dissatisfied. The ASHRAE Standard 55-1992 (ASHRAE, 1992) defines thermal comfort as satisfaction with the thermal environment by which 90% of the occupants would be thermally comfortable. To meet this requirement, a PMV of -0.5 to +0.5 has been recommended.

Table 20 - ASHRAE Thermal Sensation Scale

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	warm	hot

Since the inception of the Fanger's PMV thermal comfort model, the formulations and theories has been subjected to numerous peer reviews and validations. Within the context of this study, it is important to be aware of the limitations of the PMV model, specifically those related to the use of this model in predicting thermal comfort levels in thermal simulations.

The formulation of the Fanger's PMV model was based on data collected from laboratory and climate chamber studies, where the participants were subjected to constant conditions in a chamber for a period of time. This views occupants as passive recipients of thermal stimuli and overlooks the thermal adaption actions from occupants. Therefore, when interpreting the results generated by the Fanger's PMV model, it has to be assumed that the adaptive natures of building occupants, including psychological adaption, physiological adaptations, and behavioural thermoregulation or adjustment, were not considered.

The adaptive natures of building occupants, specifically those related to behavioural thermoregulation or adjustment, such as changing activities, clothing, putting on blankets, opening windows, and drinking cold or warm drinks, leads to dynamic conditions between the heat produced by metabolism and the heat lost from the body. However, the methodologies in determining comfort levels in simulation programs are based on steady-state conditions where predefined values have to be applied in the model and do not get updated with changing indoor environmental conditions. The prediction of PMV requires knowledge of the clothing insulation and the metabolic rate and the steady-state assumption cannot readily reflect the fluctuating metabolic rates and the clothing value with occupants. This problem is more severe in residential settings than office environments as there are more ways to adapt to the existing environment and have less predictable activities (Peeters, 2009). As well, the humidity ratio in the air might not be adequately accounted for in thermal simulation models. Moisture is generated in the house from domestic activities such as cooking and showering, and as part of the metabolic process of the occupants. Thermal simulation programs generally do not account for these sources and therefore might not provide a representative prediction on the PMV.

Although limitations occur in employing the Fanger's PMV model, it has served to be an indicator in providing thermal comfort evaluations for building spaces. With the limitations of the Fanger's PMV model acknowledged, it is important to be aware of them when evaluating Fanger's PMV results generated by thermal simulation models.

Alternatively, number of hours not within a predefined temperature range (e.g. ± 2 ^{o}C) of set-point provides a direct mean in evaluating the system's ability to meet the set-point temperature requested. Over- or under-conditioned spaces can be identified with this index

4.6 Simulation Results

4.6.1 Thermal comfort analysis

On the basis of the building characteristics described above, heating energy consumption was predicted by using EnergyPlus based on the Canadian Weather for Energy Calculations (CWEC) data file from the nearest available weather station (Toronto International Airport). In order to generate results suitable to be compared with Fanger's PMV, heating set-point and setback temperature are set to be 23^{o}C and 21^{o}C respectively. The set-point schedule is in accordance to Table 21. Setback is applied for the rest of the times.

Table 21 – Set-point schedule for single-zone system

Weekdays	05:00-09:00; 17:00-24:00
Weekends	07:00-24:00

The Basecase model is simulated from the period of January 1st to March 31st. Daily indoor temperatures are calculated by averaging the hourly indoor temperatures predicted by the thermal simulation model. The hourly minimum and maximum indoor temperatures for each day, i.e. the daily minimum and maximum are also determined. The daily average temperature along with the daily minimum and maximum for eight of the most occupied spaces for the period of January 21st to February 21st are as shown in Fig. 50-57.

The temperature profiles vary significantly from room to room and are correlated with the orientation of the rooms. Referring to the floor plan of the dwelling (Fig. 38), the living room, study room, and bedroom B are north-facing. The kitchen, family room, master bedroom, and bedroom A are south-facing and the dining room faces west and is shaded by the neighbouring dwelling.

The indoor temperatures in south-facing rooms are generally much higher. From the period of January 1st to March 31st, the average of the daily indoor temperature ranges from 23.7^{o}C to 24.0 ^{o}C for south-facing rooms. This is on average 2°C higher than that of average indoor temperatures in north-facing rooms, where it is in the range of 21.7 °C to 22.3 °C. The minimum of the daily indoor air temperature during that period in south-facing rooms is 22.7 °C, as oppose to 21.6 °C for north-facing rooms. On the other hand, the maximum of the daily indoor air temperature in south-and north-facing rooms are 25.4 °C and 22.7 °C respectively. Hourly maximum can go up to 27.8 °C in south-facing rooms, as opposed to 23.6 °C in north-facing rooms.

In addition to the higher temperature predicted in south-facing rooms, temperature fluctuates in a much larger degree in south-facing rooms than north-, and west-facing rooms. In south-facing rooms, the indoor air temperature can vary up to 3.11 °C for daily minimum and 2.69 °C for daily maximum. On the other hand, the indoor air temperature only vary up to 1.55 °C for daily minimum and 1.20 °C for daily maximum in north-facing rooms. The indoor temperature in north-, and west-facing rooms are generally more stable. Table 22 and 23 below summarizes the results.

Table 22 - Indoor air temperatures for Basecase model

		Daily Indoor Air Temperature (°C)			Hourly Indoor Air Temp (°C)	
		Average	Min	Max	Min	Max
South-facing	Kitchen	23.8	22.7	25.1	21.4	27.8
	Family Room	23.7	22.8	25.2	21.6	27.4
	Bedroom A	24.0	23.1	25.4	21.8	27.8
	Master Bedroom	23.7	23.0	24.8	21.8	26.6
North-facing	Living Room	21.7	21.6	22.2	20.7	22.8
	Bedroom B	22.3	22.0	22.7	20.8	23.6
	Study Room	22.2	22.0	22.5	20.8	23.3
West-facing	Dining Room	22.3	22.0	23.1	20.9	25.4

Table 23 – The maximum of indoor air temperatures fluctuations for Basecase model

		Daily Minimum (°C)	Daily Maximum (°C)
South-facing	Kitchen	3.11	2.69
	Family Room	2.90	2.41
	Bedroom A	2.84	2.45
	Master Bedroom	2.44	1.87
North-facing	Living Room	1.49	1.07
	Bedroom B	1.55	1.20
	Study Room	1.51	1.16
West-facing	Dining Room	2.08	2.60

Fig. 50-57 illustrates that south-facing rooms are much more sensitive to solar radiation. Following days of high global solar radiation, indoor air temperature rises rapidly in south-facing rooms. For instance, indoor air temperature in the kitchen rises from 23 °C to 25 °C from February 2nd to 5th, whereas in north-facing rooms, the temperature remains relatively steady during that period.

In a single-zone system, the master thermostat depicts whether heating or cooling is required for the entire dwelling, disregarding thermal load differences in the different rooms being conditioned. The master thermostat in Basecase is located in the living room, which is a north-facing room. North-facing rooms receive much less passive solar heat gain throughout the year and therefore have to rely heavily on mechanical heating to help satisfy the heating load. Central heating therefore has to operate frequently to supply heating to the living room in order to satisfy the heating set-points. During operation, heating is also supplied to all the other room including those faces south. Since south-facing rooms receive much higher passive solar heat gain, these rooms are frequently being overheated and are therefore much more sensitive to global solar radiation.

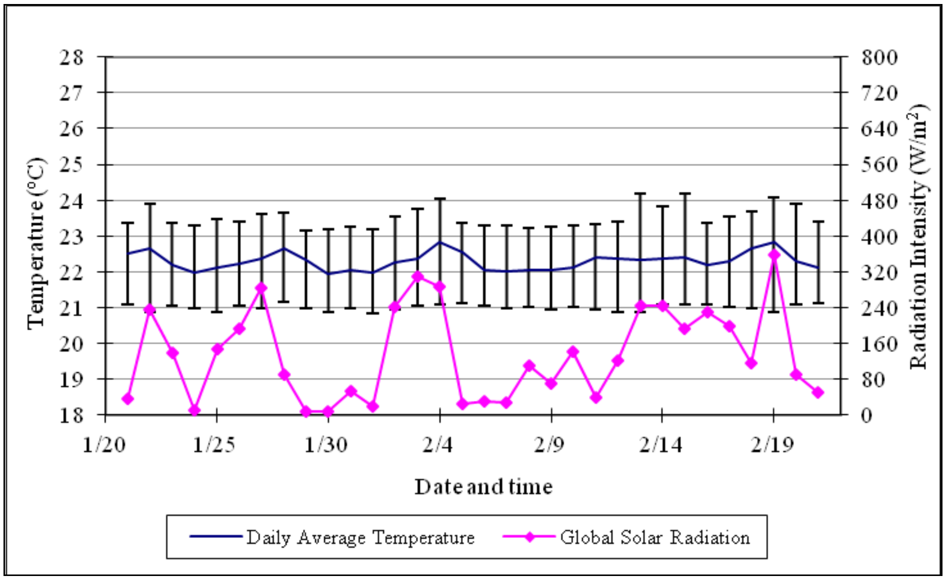

Figure 50 - Dining Room air temperature with single-zone system

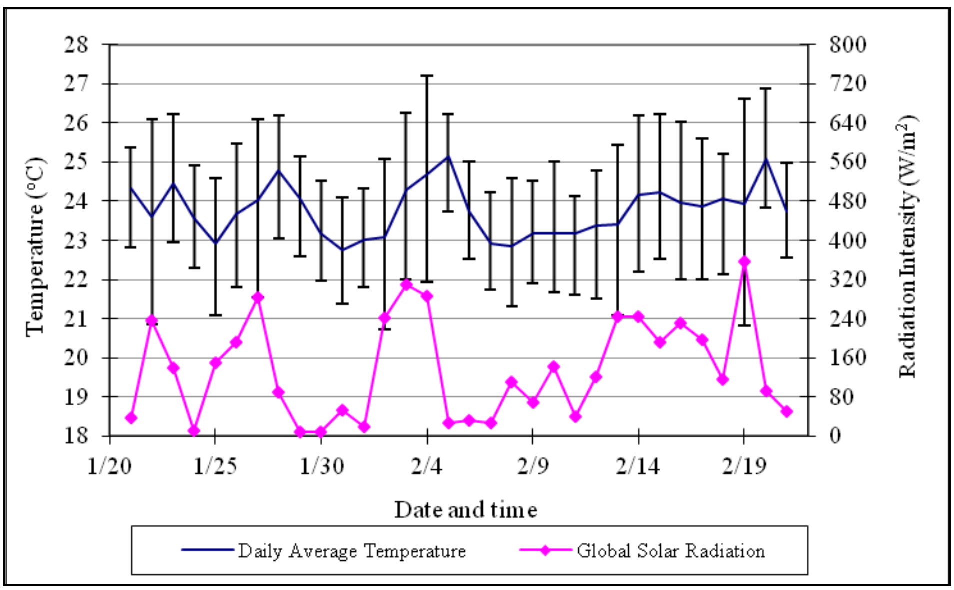

Figure 51 - Kitchen air temperature with single-zone system

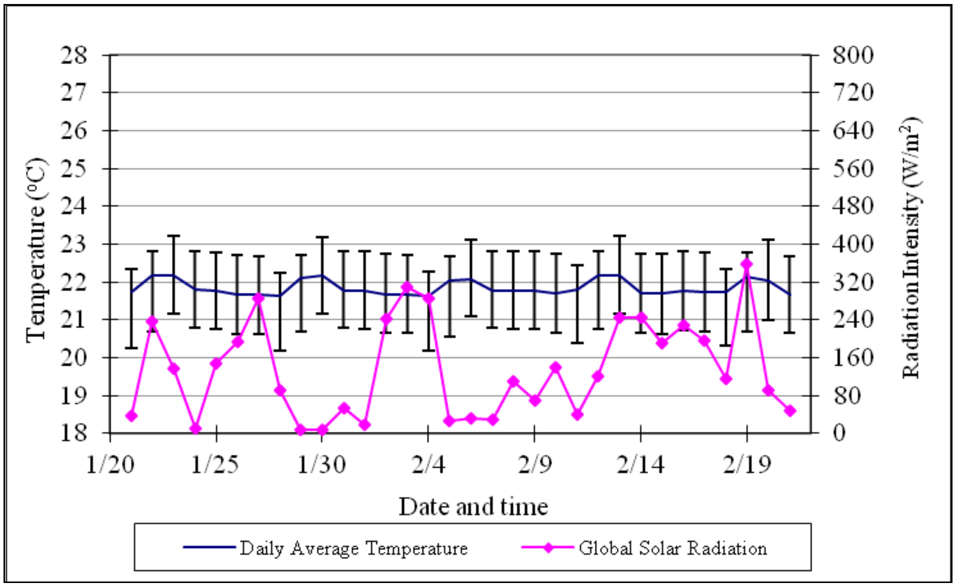

Figure 52 – Living Room temperature with single-zone system

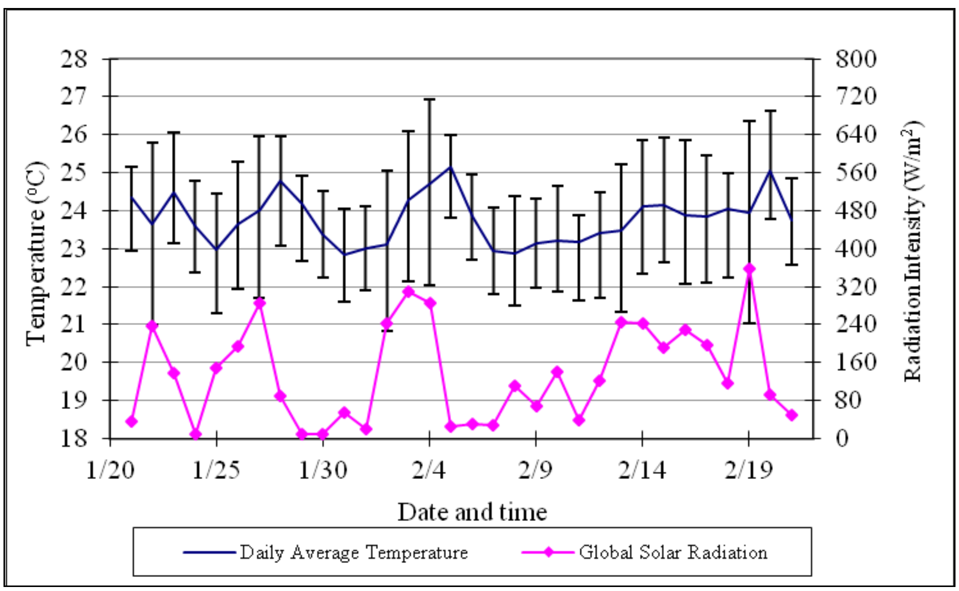

Figure 53 – Family Room air temperature with single-zone system

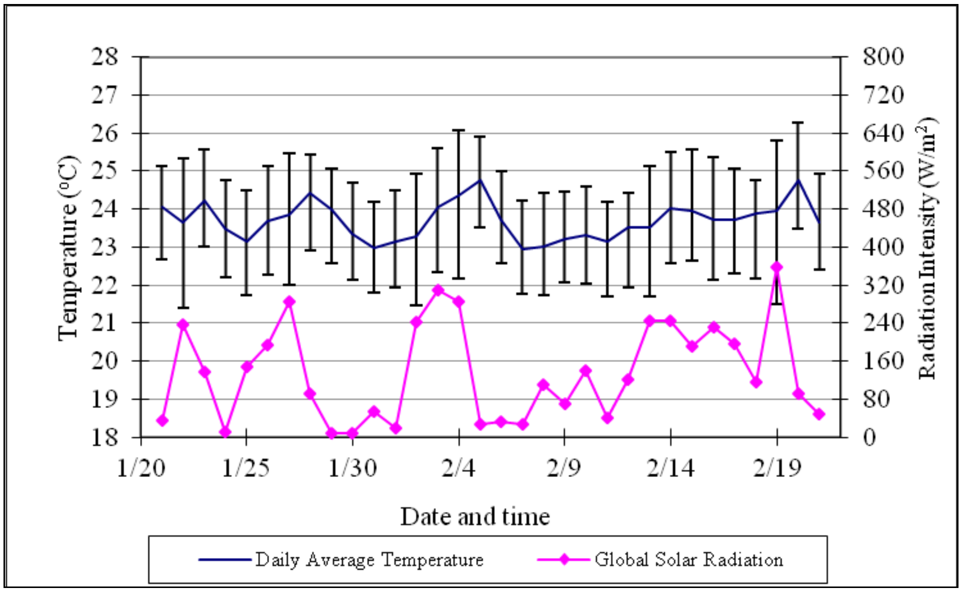

Figure 54 – Master Bedroom air temperature with single-zone system

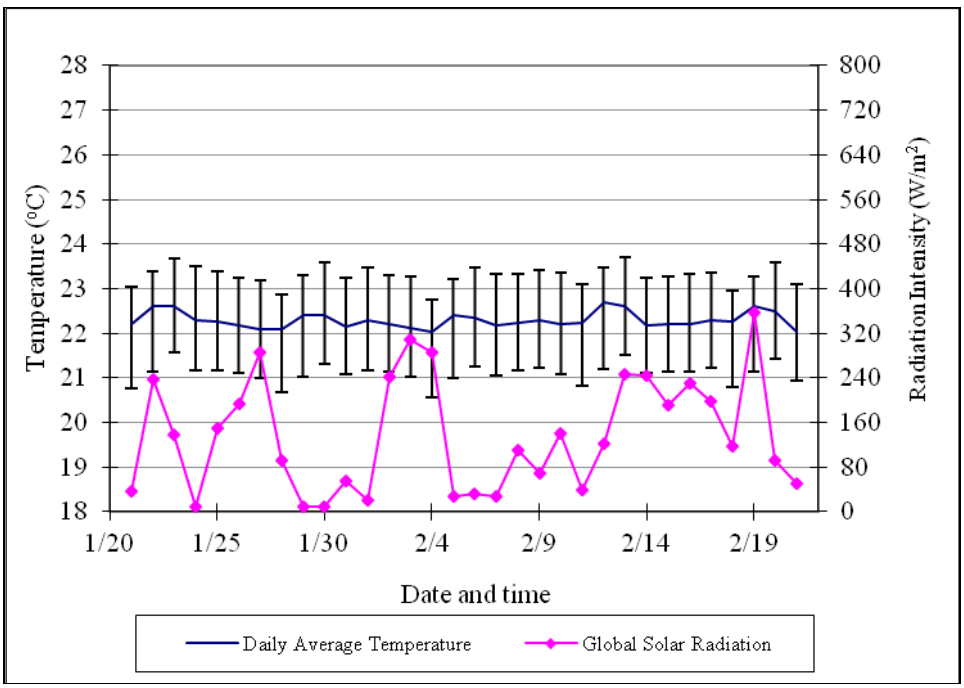

Figure 55 – Bedroom B air temperature with single-zone system

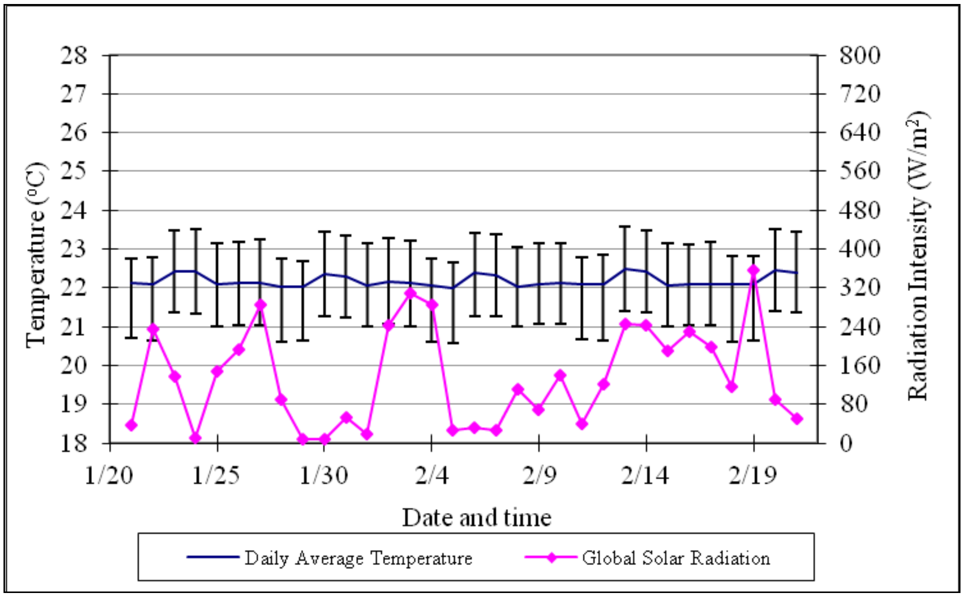

Figure 56 – Study Room air temperature with single-zone system

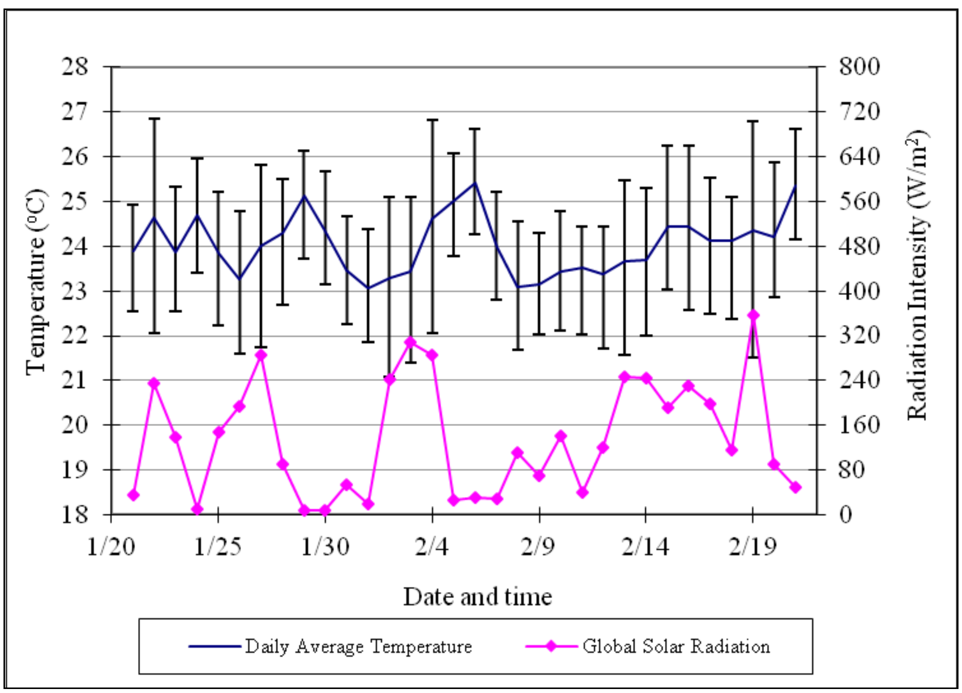

Figure 57 – Bedroom A air temperature with single-zone system

The Fanger's PMVs are determined for the period from January 21st to February 21st and are as illustrated in Fig. 58 for rooms on the first-floor and Fig. 59 for second-floor's room. The Fanger's PMV are relatively low for all eight rooms, which is in contrary to the previous discussion where indoor air temperatures in south-facing rooms are significantly higher than north-facing rooms. This discrepancy is due to the low relative humidity predicted by the thermal simulation model. Therefore, although in all instances, the simulated PMV in south-facing rooms is much closer to neutral than west- and north-facing rooms, it cannot be concluded that south-facing rooms are more thermally comfortable than north-facing rooms. Nonetheless, Figures 58 and 59 shows that the single-zone system leads to wide thermal comfort distributions across the dwelling with differences as large as 1 PMV in some instances.

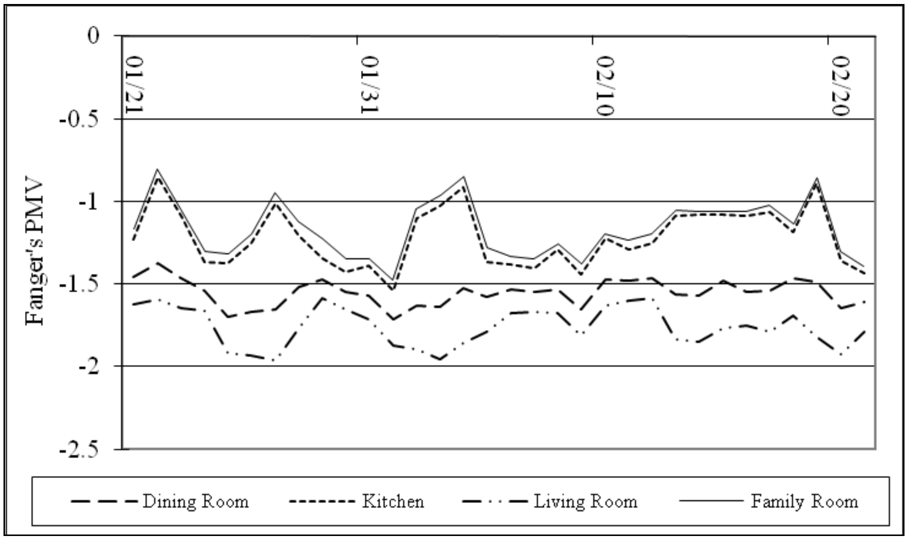

Figure 58 – First Floor's Fanger's PMV with single-zone system

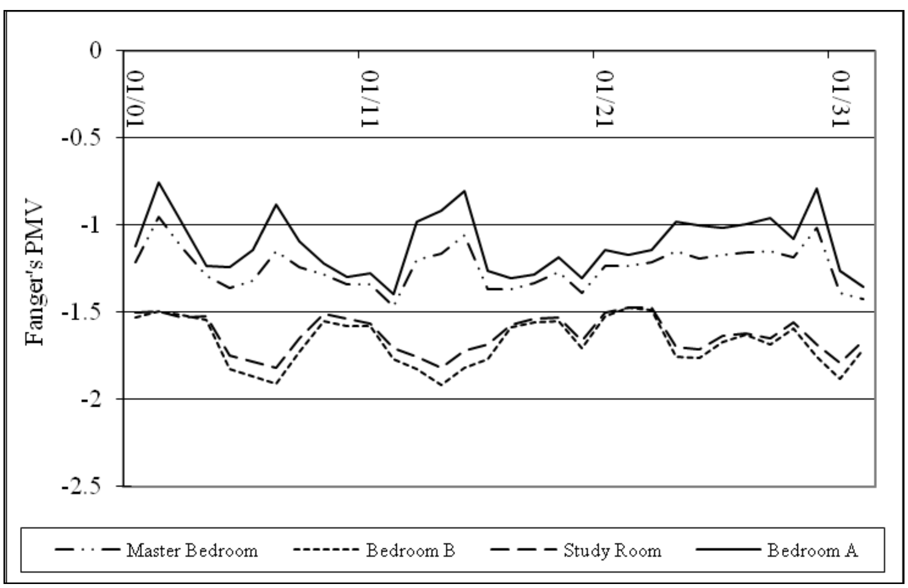

Figure 59 – Second Floor's Fanger's PMV with single-zone system

On the basis of the above analyses, the total number of hours where the indoor air temperature is not within +/- 2°C of set-points is then determined and is divided by the total number of hours under investigation, which is 2160 hours (Fig. 60). As expected, all south-facing rooms are over-conditioned. Specifically, bedroom A on the second-floor is overheated 724 hours out of the 2160 hours, or 33.5%. The master bedroom, family room, and kitchen are overheated 19.3%, 23.9%, and 25.7% of the 2160 hours being investigated respectively. All the north-facing rooms on the other hand, are all able to be maintained within the +/- 2°C set-point range relatively well.

This illustrates that the current system over-conditions certain spaces, which corresponds to the survey findings where 38.5% of the respondents indicated they experience overheating and approximately 14% experiences overheating daily or more frequently in their dwelling. This system arrangement relies on a master thermostat to regulate temperature throughout the dwelling and could not take the different thermal loads in different rooms into account.

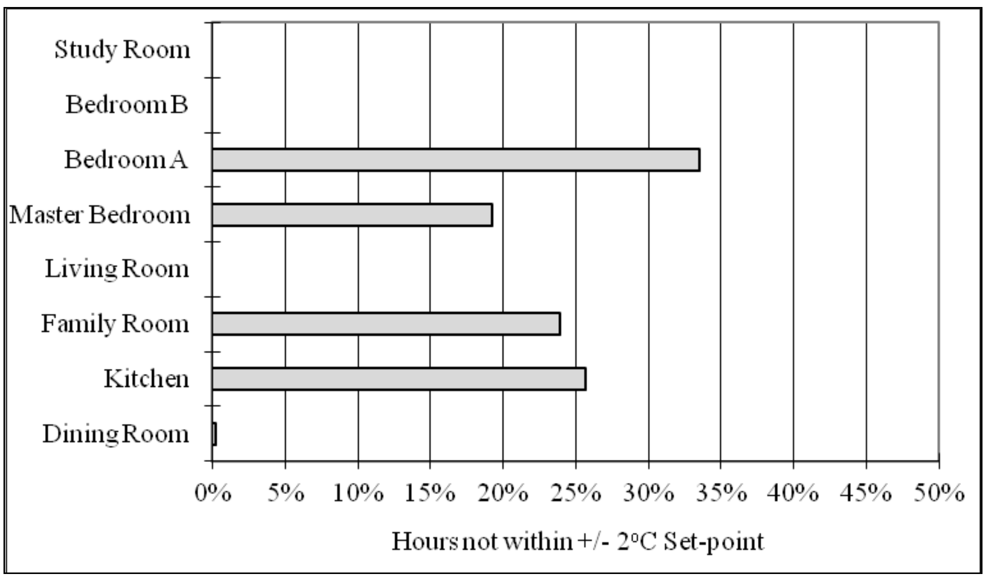

Figure 60 –Hours not within ±2°C of set-point using a single-zone system

Thermal simulation was crucial in identifying and evaluating the potential deficiency of the current system. With the above analyses, it can be concluded that temperature homogeneity could not be achieved with the as-built configuration. The current heating system could not take the difference in heating load into account and therefore resulted in overheating in certain spaces of the dwelling.

As an alternative, multi-zone systems may provide a platform to effectively condition various zones within a house while significantly reducing the overall energy consumption. The multi-zone system as described in Section 4.4.2 is then simulated to evaluate the potential benefits the multi-zone system can deliver. The multi-zone system places individual thermostats in each of the conditioned rooms and the thermostats are configured to better represent the occupancy schedules. The occupant will gain additional control of interior temperature to overcome comfort dissatisfaction.

The thermostat settings in each space are as summarized in Table 24. Similar to the single-zone system, heating set-point and setback temperature are set to be 23°C and 21°C respectively. The set-point schedule is in accordance to Table 24. Setback is applied for the rest of the times.

Table 24 – Set-point schedule for multi-zone system

	Weekdays	Weekends
Dining Room	05:00-09:00; 16:00-20:00	07:00-11:00; 12:00-14:00; 17:00-21:00
Kitchen	05:00-09:00; 15:00-19:00	07:00-11:00; 12:00-14:00; 16:00-20:00
Family Room	16:00-23:00	08:00-24:00
Living Room	16:00-23:00	08:00-24:00
Master Bedroom	24:00-09:00; 19:00-24:00	24:00-11:00; 20:00-24:00
Bedroom A	24:00-09:00; 19:00-24:00	24:00-11:00; 20:00-24:00
Washroom	05:00-09:00; 20:00-23:00	07:00-10:00; 13:00-16:00; 19:00-22:00
Bedroom B	24:00-09:00; 19:00-24:00	24:00-11:00; 20:00-24:00
Study Room	17:00-23:00	-
Master Washroom	05:00-09:00; 20:00-23:00	07:00-10:00; 13:00-16:00; 19:00-22:00

The model is revised with the upgraded heating equipment and the updated operational schedules. The daily average temperature along with the daily minimum and maximum for eight of the most occupied spaces for the period of January 21st to February 21st are as shown in Fig. 61-68.

As seen, the indoor temperatures in south-facing rooms are comparable to that of north-facing rooms. From the period of January 1st to March 31st, the average of the daily indoor temperature ranges from 22.0°C to 22.6 °C for south-facing rooms. This is 1.2°C – 1.8 °C lower than that of single-zone systems. Average indoor temperatures in north-facing rooms range from 21.6 °C to 22.1 °C. The minimum of the daily indoor air temperature during that period in south-facing rooms is 18.9 °C, as oppose to 18.1 °C for north-facing rooms.

On the other hand, the maximum of the daily indoor air maximum can go up to 24.7 °C in south-facing rooms, as opposed to 22.7 °C in north-facing rooms.

The indoor air temperatures generally fluctuate more than that of Basecase. For instance, the indoor air temperature can vary up to 3.70 °C for daily minimum and 3.93 °C for daily maximum in the kitchen, as oppose to 3.11 °C and 2.69 °C for Basecase. The daily minimum and maximum for the rest of the south-facing rooms is comparable to that of Basecase. On the other hand, the indoor temperatures in north-facing rooms generally fluctuate more than that of Basecase. Table 25 and 26 below summarizes the results. The temperatures in the rooms are individually controlled and are configured to better represent the occupant activities in different rooms. For instance, in the study room, as opposed to being conditioned to the set-point temperature for four hours in the morning and seven hours at night every weekday, the study room is only being conditioned for six hours every weekday with the multi-zone system. Since the room is being conditioned to the set-point temperature in a shorter period of time, the temperature fluctuates more than Basecase.

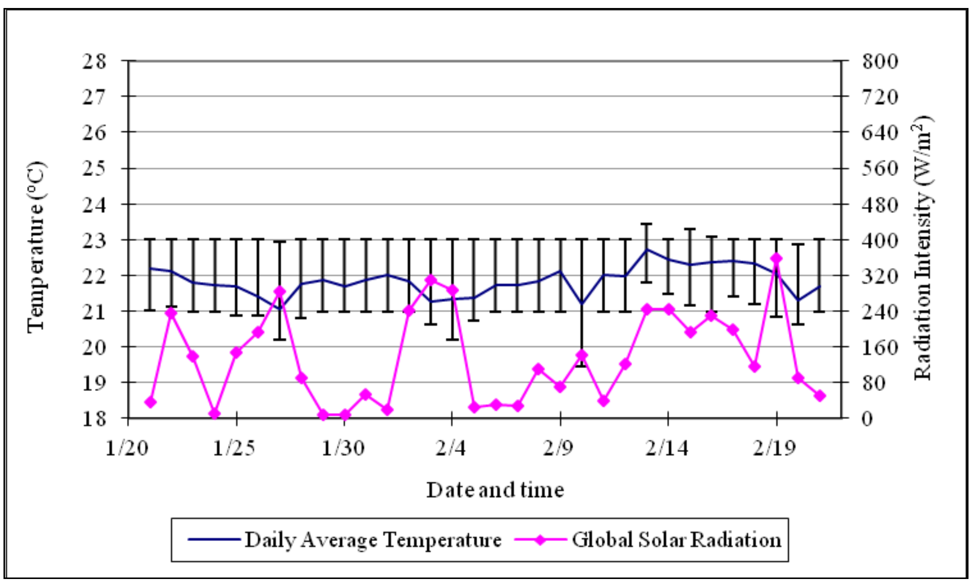

Figure 61 - Dining Room air temperature with multi-zone system

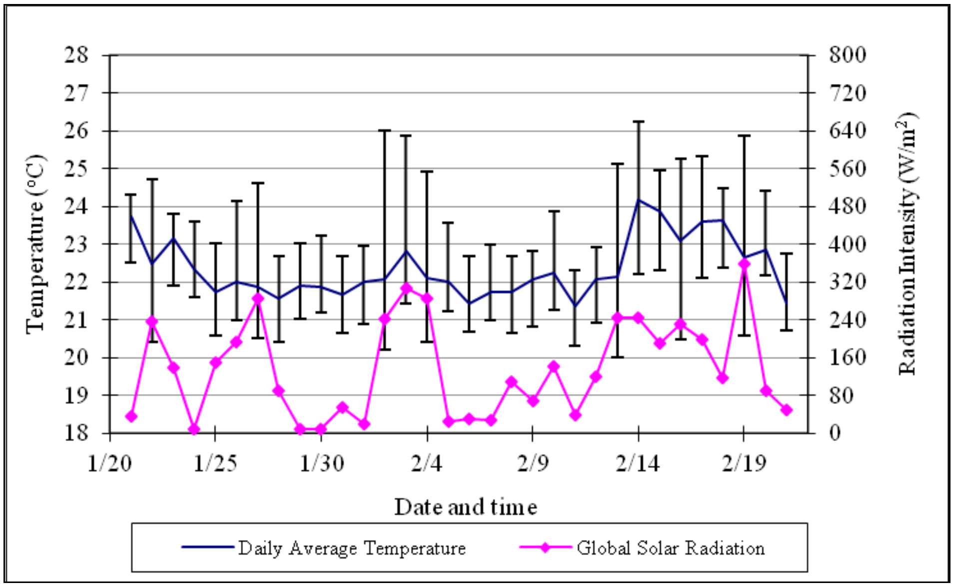

Figure 62 - Kitchen air temperature with multi-zone system

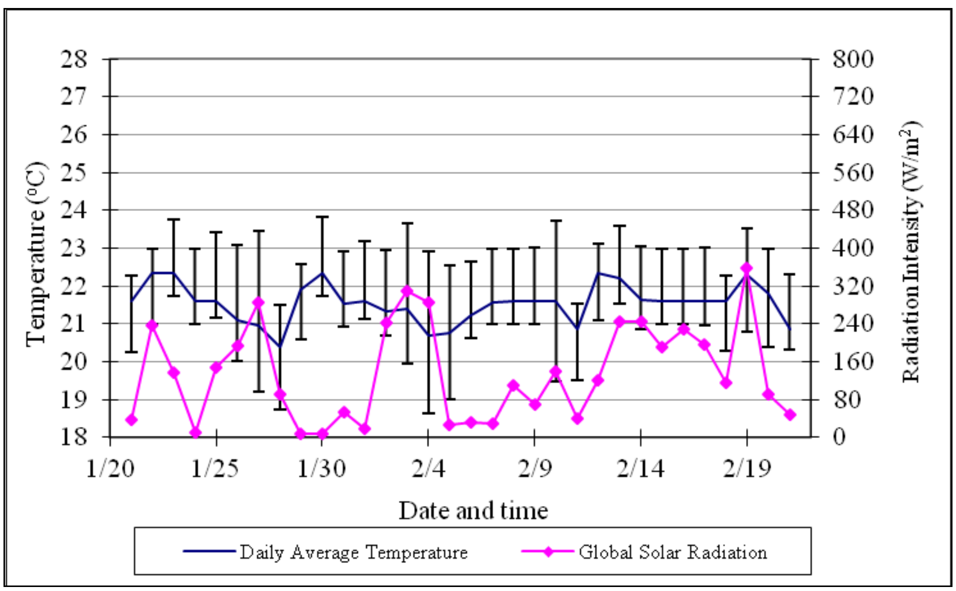

Figure 63 – Living room air temperature with multi-zone system

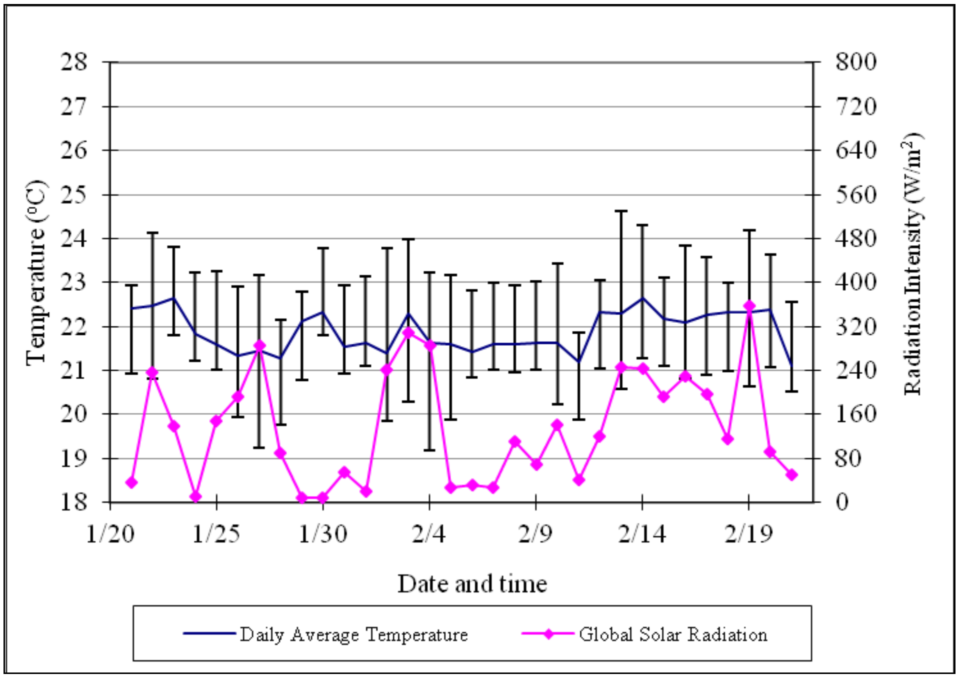

Figure 64 – Family room air temperature with multi-zone system

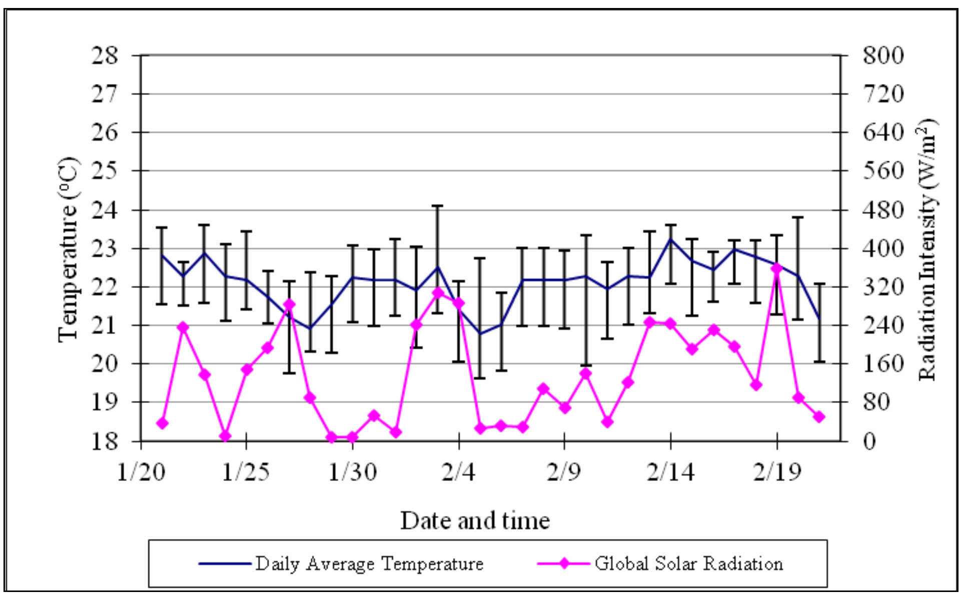

Figure 65 – Master bedroom air temperature with multi-zone system

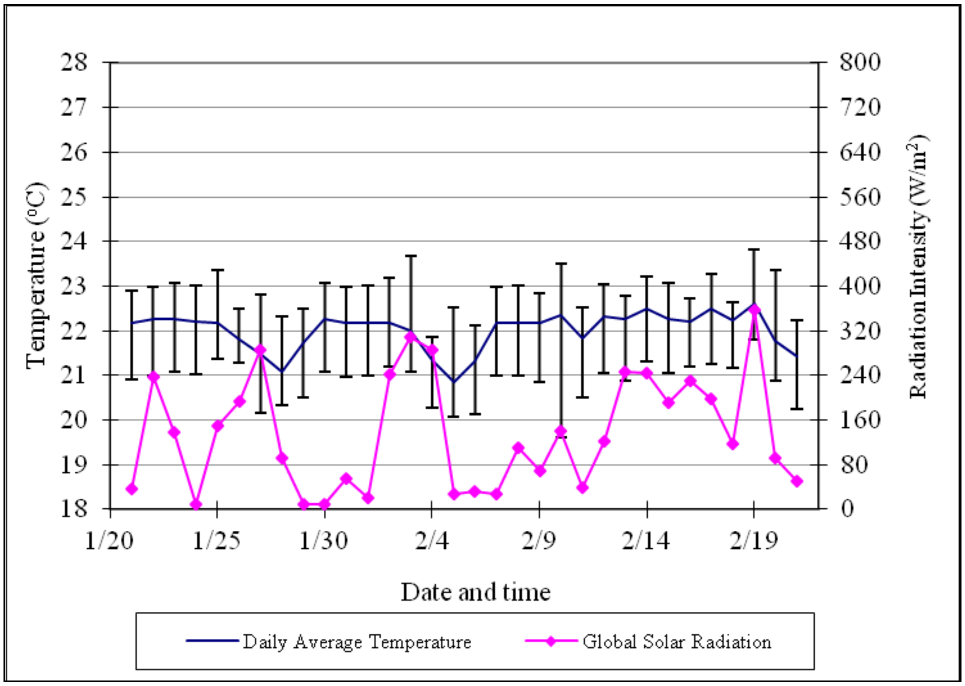

Figure 66 –Bedroom B air temperature with multi-zone system

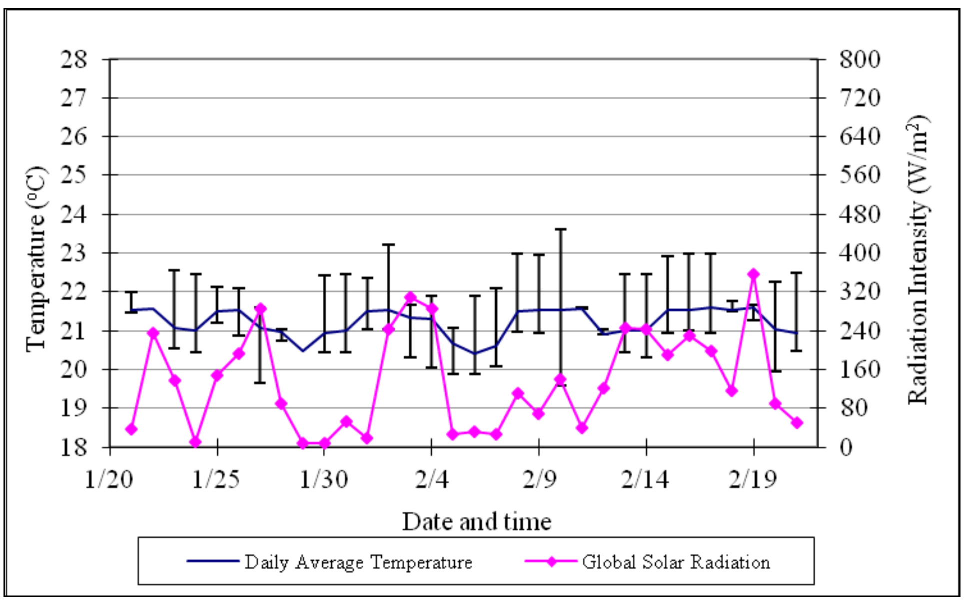

Figure 67 – Study room air temperature with multi-zone system

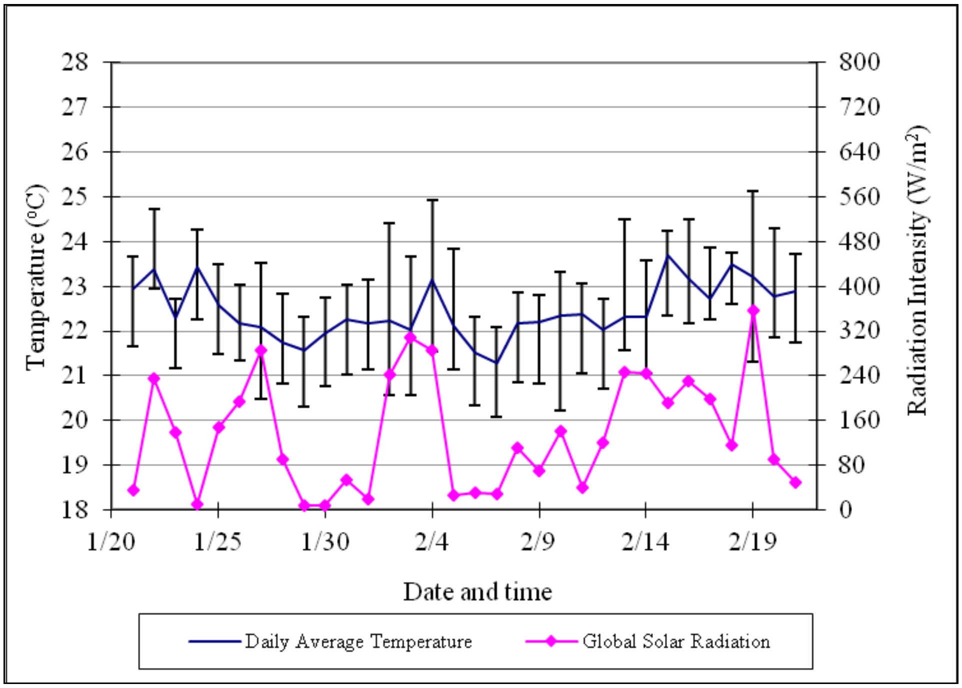

Figure 68 –Bedroom A air temperature with multi-zone system

Table 25 - Indoor air temperatures for upgraded model

		Daily Indoor Air Temperature (^oC)			Hourly Indoor Air Temp (^oC)	
		Average	Min	Max	Min	Max
South-facing	Kitchen	22.6	20.5	24.7	20.2	27.2
	Family Room	22.0	19.2	23.2	19.1	25.2
	Bedroom A	22.5	19.5	24.1	19.7	25.9
	Master Bedroom	22.3	18.9	23.4	19.3	24.4
North-facing	Living Room	21.6	18.1	22.4	21.0	23.0
	Bedroom B	22.1	18.9	22.7	19.1	23.0
	Study Room	21.3	18.1	21.6	19.0	23.0
West-facing	Dining Room	22.0	19.8	23.0	19.4	24.8

Table 26 – The maximum of indoor air temperatures fluctuations for upgraded model

		Daily Minimum (^oC)	Daily Maximum (^oC)
South-facing	Kitchen	3.70	3.93
	Family Room	2.46	2.40
	Bedroom A	2.12	2.20
	Master Bedroom	2.31	1.98
North-facing	Living Room	2.24	2.47
	Bedroom B	2.74	1.89
	Study Room	1.95	2.08
West-facing	Dining Room	2.02	1.92

With this configuration, the Fanger's PMV in south-facing rooms generally corresponds to that in north-facing room (Fig. 69-70). South-facing rooms are still generally more sensitive to global solar radiation (Fig. 62, 64-65, 68), and the Fanger's PMV predicted is in agreement to that. During periods of high global solar radiation, the predicted PMV is generally higher in south-facing room than in north-facing rooms. For instance, from the period of February 13th February 17th, the average PMV of the kitchen and family room are -0.89 and -1.11, where -1.41 is recorded in the north-facing living room during that period.

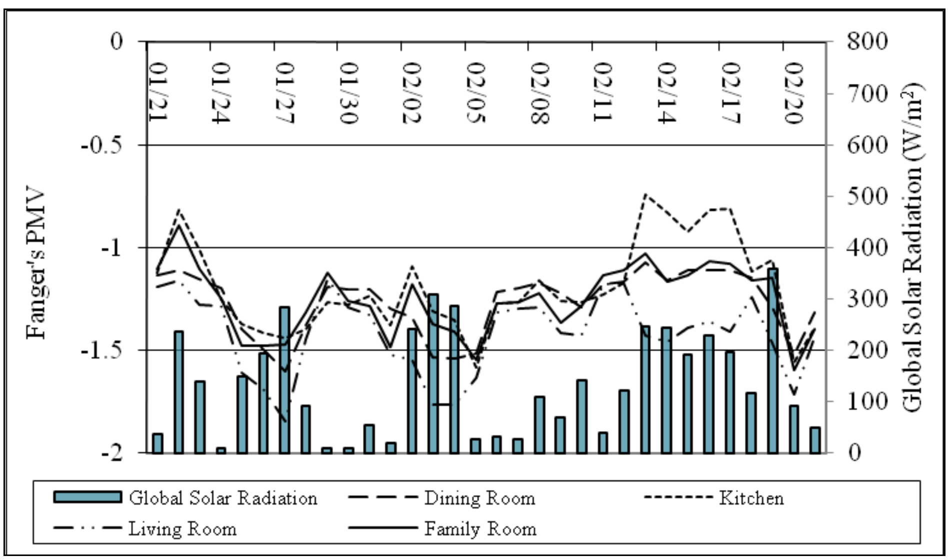

Figure 69 – First Floor's Fanger's PMV with multi-zone system

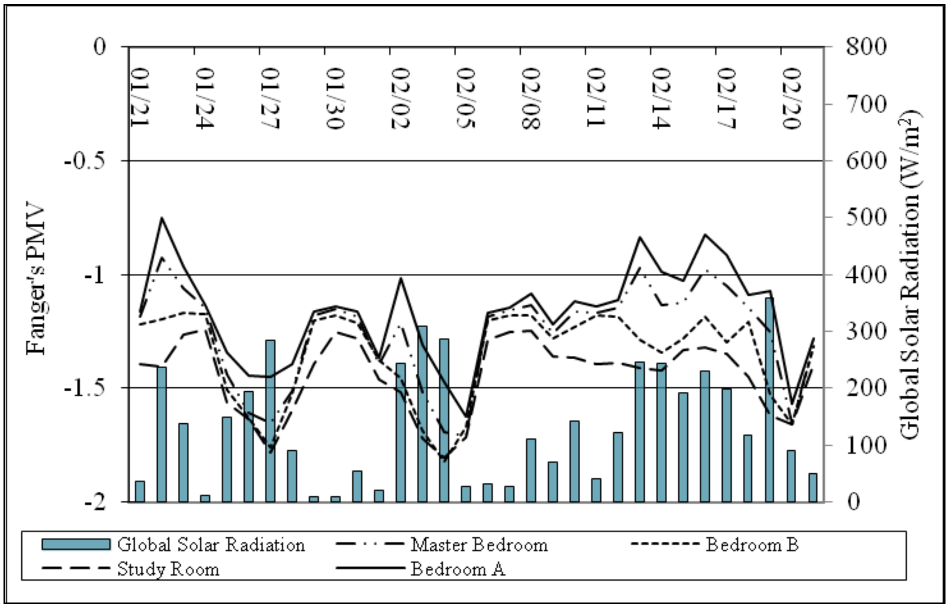

Figure 70 – Second Floor's Fanger's PMV with multi-zone system

The occurrences of overheating are significantly reduced in south-facing rooms as a result of employing a multi-zone system (Fig. 71). The number of hours overheating, or hours not within +2^{o}C set-point is reduced by 37.3%, 83.2%, 73.1%, and 68.5% in kitchen, family room, master bedroom, and bedroom A respectively. The reduction is lowest in the kitchen, which has the largest window-to-floor area ratio (Table 27). As mentioned, rooms are still sensitive to global solar radiation and therefore there is a larger tendency for overheating to occur with larger window areas.

On the other hand, with the multi-zone system, all rooms experience insufficient heating, or hours not within -2^{o}C set-point occasionally. Insufficient heating occurs more frequently in second-floor rooms. The average number of hours not within -2^{o}C set-point is 92 hours for second-floor rooms and 68 hours for first-floor rooms. This is partially due to the greater amount of heat loss through the envelope in second-floor rooms.

The combination of reduction in overheating and increase in insufficient heating results in a reduction in total number of hours not within +/- 2^{o}C set-point by 29.5%, 71.4%, 44.2%, and 56.5% in kitchen, family room, master bedroom, and bedroom A respectively. The total number of hours not within +/- 2^{o}C set-point for the entire dwelling is reduced by 33.8%, or from 2,216 hours to 1,467 hours.

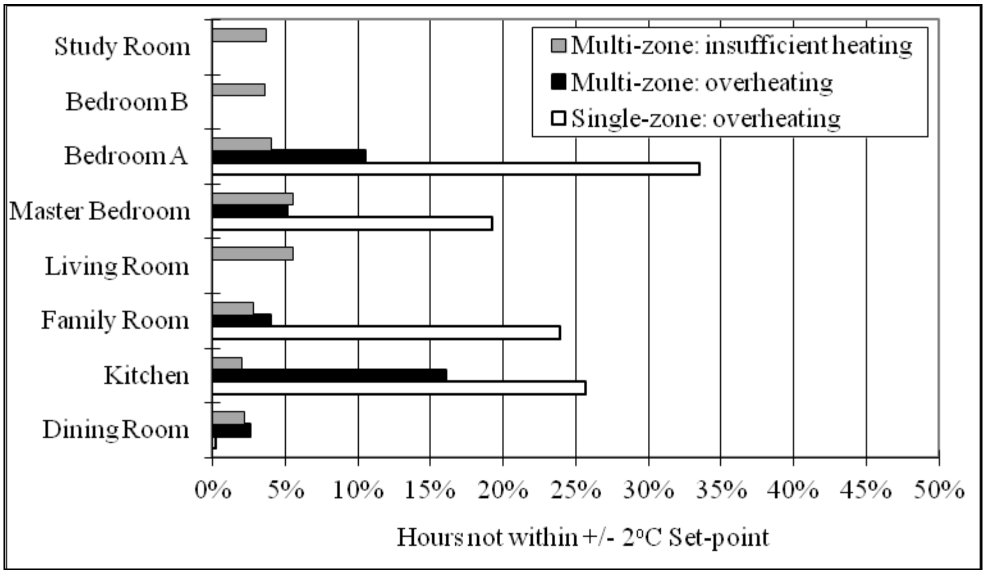

Figure 71 –Hours not within ±2°C of set-point

Table 27 - Window-to-floor area of south-facing rooms

	Floor area (m^2)	Window area (m^2)	Window-to-floor area ratio
Kitchen	19.93	5.29	0.265
Family Room	15.33	2.15	0.140
Master Bedroom	29.68	4.53	0.153
Bedroom A	15.7	2.59	0.165

4.6.2 Energy consumption analysis

The single-zone system led to inefficient heating because it does not take the difference in thermal loads in different rooms into account, and therefore leads to excessive overheating in south-facing rooms. The master thermostat also could not reflect the difference in activities in different rooms and therefore supply conditioned air to unoccupied rooms throughout the year. Figures 72 to 79 illustrate the hourly temperature profile and sensible heating energy for the period of January 20th to January 21st, where January 20th is a Friday and January, 21st is a Saturday. The hourly sensible heating energy is defined as the heating energy in Joules that is supplied by the HVAC system to that zone for that hour. It is calculated by multiplying the simulation timestep (one hour) by the sensible heating rate (W).

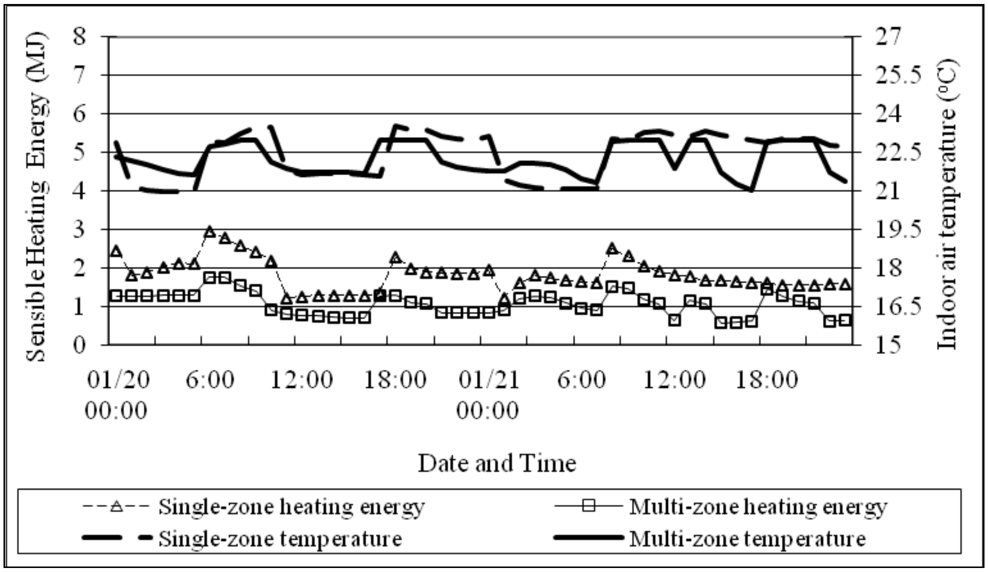

Figure 72 - Dining room: Heating energy supplied by the single- and multi-zone systems

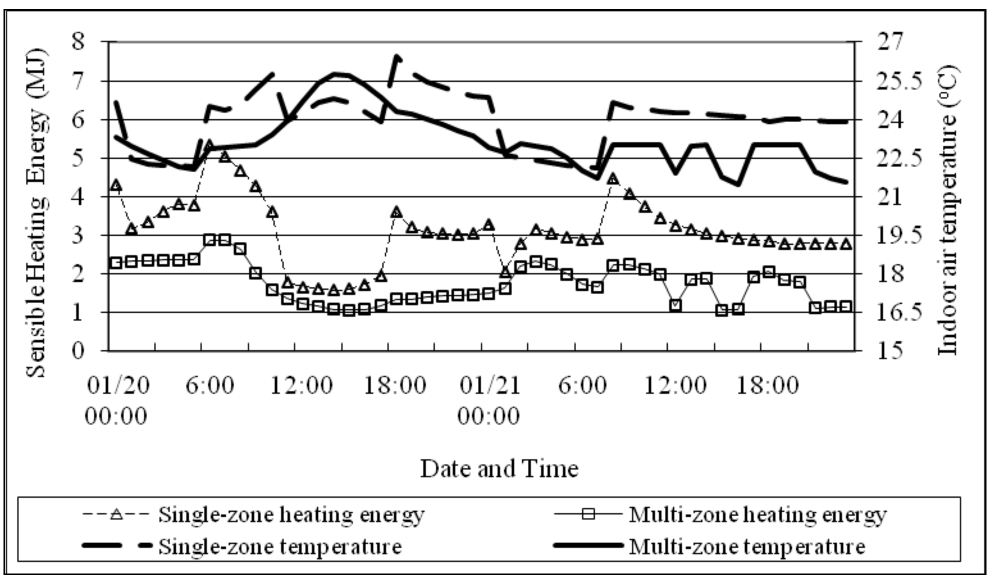

Figure 73 –Kitchen: Heating energy supplied by the single- and multi-zone systems

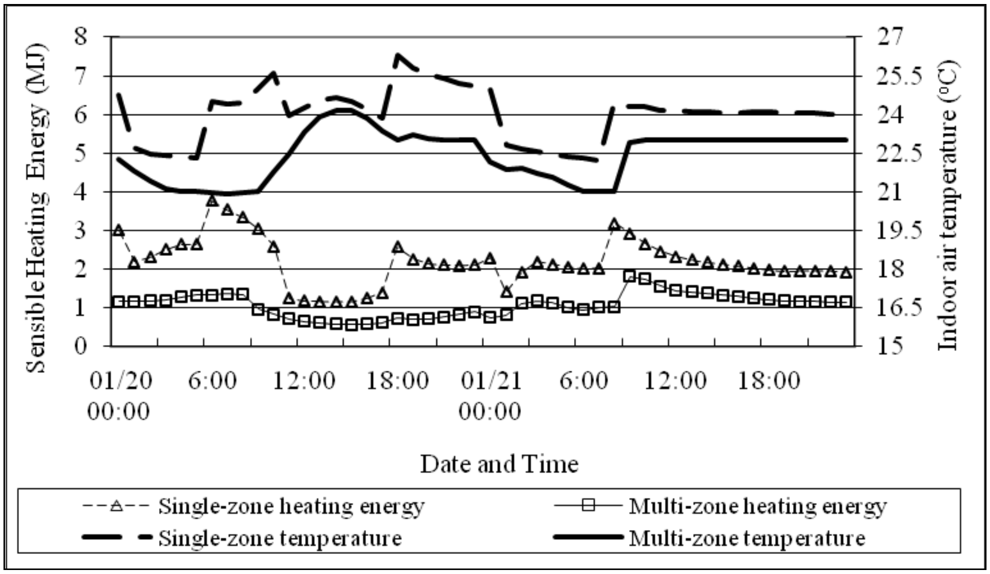

Figure 74 -Family Room: Heating energy supplied by the single- and multi-zone systems

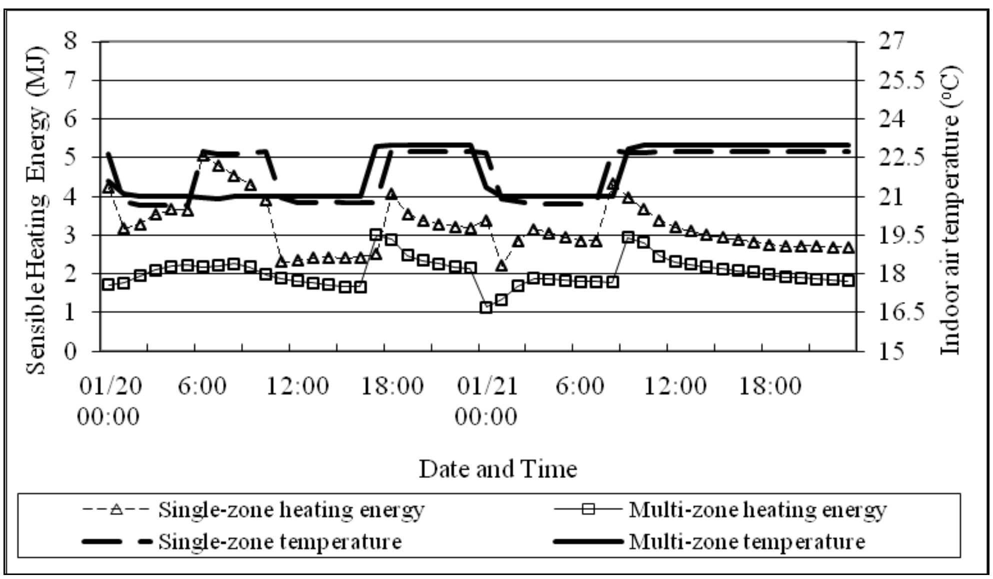

Figure 75 -Living Room: Heating energy supplied by the single- and multi-zone systems

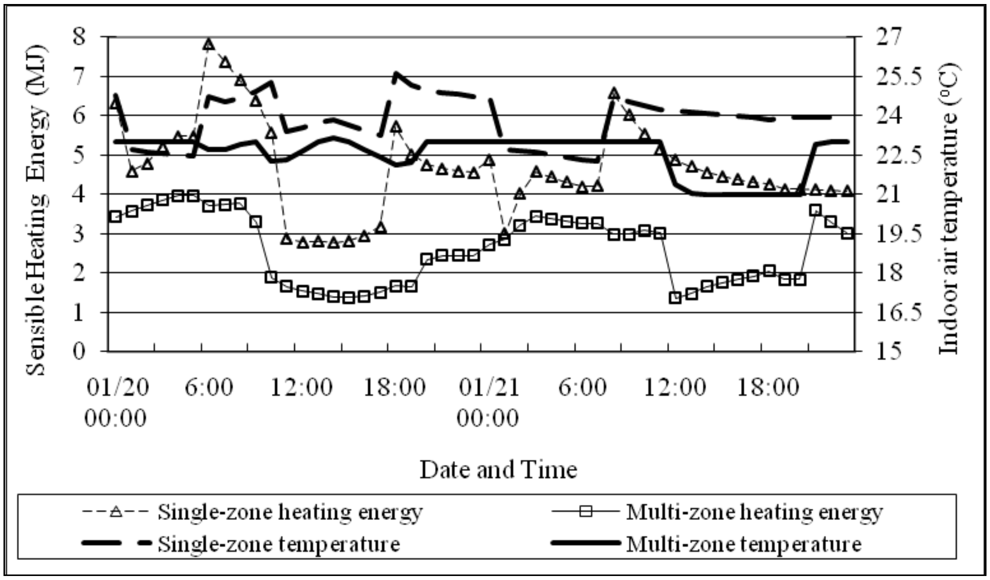

Figure 76 - Master bedroom: Heating energy supplied by the single- and multi-zone systems

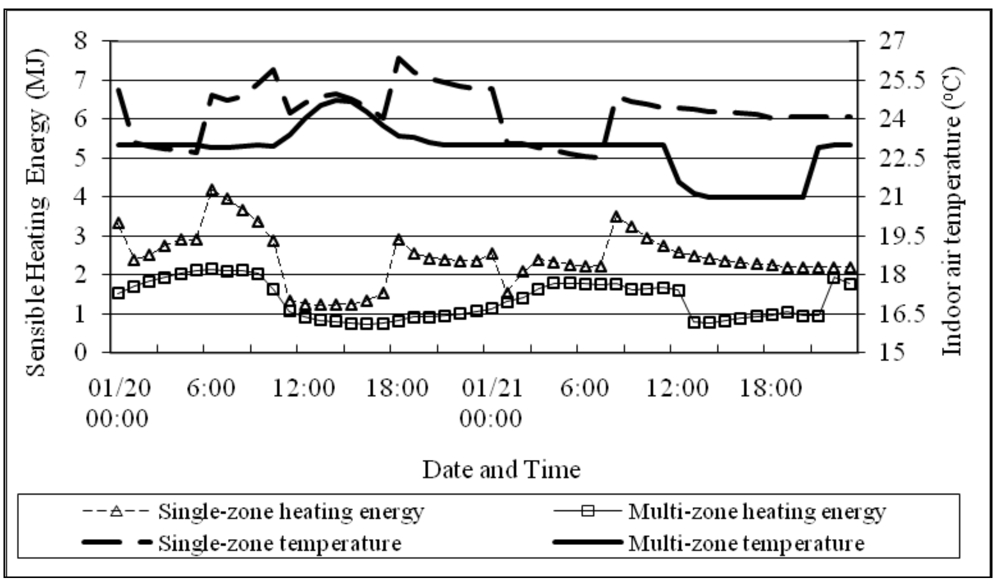

Figure 77 -Bedroom B: Heating energy supplied by the single- and multi-zone systems

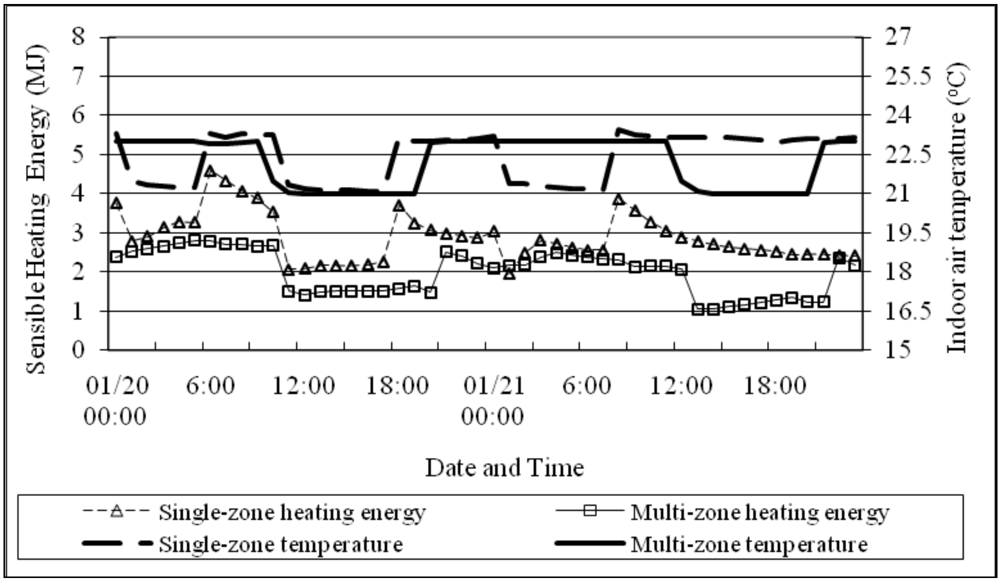

Figure 78 -Bedroom A: Heating energy supplied by the single- and multi-zone systems

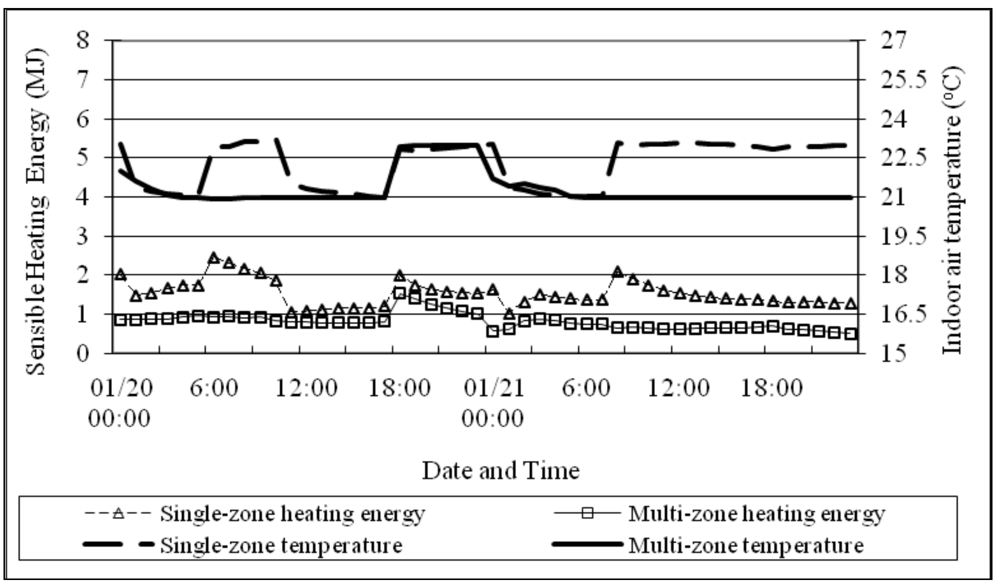

Figure 79 - Study room: Heating energy supplied by the single- and multi-zone systems

In addition to improving thermal comfort, the multi-zone system delivers increased energy efficiency. The thermostat in each room allows the occupant to set temperature back whenever the room is not occupied. For instance, in the study room (Fig. 79), the room is only occupied from 21:00-23:00 during weekdays and not occupied at all during weekends, as illustrated in Table 17. The single-zone system however, supplies heated conditioned air to this room in accordance to the master thermostat settings. This causes the room to be heated until it reaches the thermostat set-point (23^{o}C) for periods that the room is unoccupied. This leads to a higher amount of energy being supplied to the room throughout the day when compared to employing a multi-zone system.

On top of energy being wasted from conditioning unoccupied rooms, the inability of the master thermostat to react to individual room's thermal load also results in inefficient heating. In the kitchen (Fig. 73), family room (Fig. 74), master bedroom (Fig. 76), and bedroom A (Fig. 78), the indoor air temperature is well above the set-point temperature in most instances. And yet the heating energy supplied to these rooms is in accordance to the master thermostat settings, causing overheating excessively in these south-facing rooms. The multi-zone system on the other hand, prevents the rooms from being overheated by supplying adequate amounts of conditioned air to the individual rooms to meet the corresponding set-point temperature . For instance, with the multi-zone system, bedroom A (Fig. 78) is configured to be heated up to set-point (23^{o}C) from 19:00 on January 20th to 11:00 the next morning. Fig. 78 shows that the temperature in this room is constantly being maintained around 23^{o}C in that 16 hours time span. On the other hand, with the single-zone system, the room is configured to be heated up to set-point from 17:00-24:00 on January 20th and 07:00-24:00 the next day. Figure 8 shows that at 17:00 on January 20th, the air temperature in this room is already at approximately 24^{o}C, and the temperature is further raised to almost 27^{o}C at 18:00 by the central heating system and passive solar heat gain. The master thermostat, which is located at the living room, needs to reach set-point and therefore calls for heating for the entire house. As a result, bedroom A and the rest of the south-facing rooms are overheated, and resulting in a great deal of energy being consumed inefficiently.

The daily heating energy consumption from January to March for the single- and multi-zone systems are predicted by the thermal simulation model and are as illustrated in Fig. 80. Heating energy consumption is reduced by 43.1% to 44.5% for the three months (Table 28). The multi-zone system consumes much less energy than that of the single-zone system throughout the winter months.

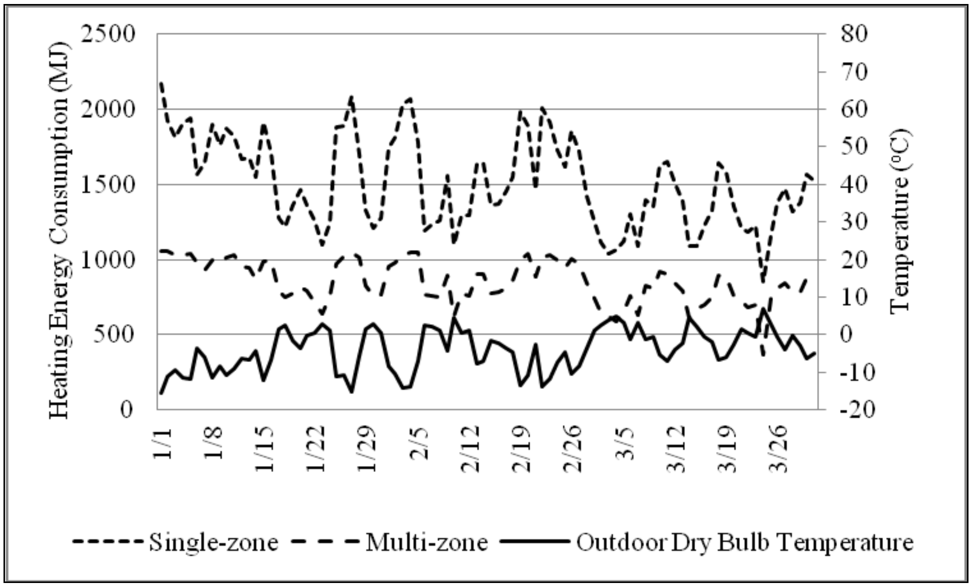

Figure 80 - Heating energy consumption comparison

Table 28 - Heating Energy Consumption (MJ)

	Single-zone	Multi-zone	Percentage Saving
January	50507	28358	43.9%
February	45000	25160	44.1%
March	40514	23180	42.8%
Total	136021	76698	43.6%

4.7 Concluding remarks

The energy requirements of buildings will continue to increase as new and existing building stocks continue to grow. Currently many existing buildings are inhabited and operated without consideration of strategies that could, in many cases, help improve the overall performance. To provide substantial improvements in energy consumption and comfort levels to existing buildings, there is a need to subject these buildings to comprehensive evaluations. The benefits of conducting thermal simulation studies during the post-occupancy phase of a building are made clear with the above discussions.

Prior to the thermal simulation study, a POE in the form of a full-scale survey was conducted with 398 Ontarioians residing in low-rise residential buildings. POE is imperative to a systematic and comprehensive evaluation of building performances and is a crucial step in identifying deficiencies of the existing system. Educational programs should be carried out to educate the industry the benefits and opportunities POE can bring to the well-being and value of their properties. A partnership between the government and industry should be established in promoting the adoption of POE. Government support in the form of monetary incentives or tax credits would help provide the industry with necessary resources. Additionally, government legislations in the form of mandatory or voluntary regulations would help promote POE to be conducted. Furthermore, in this chapter of the thesis, it was shown that by using as-built drawings and operational schedules provided by occupants, a thermal simulation model can be established and the accuracy of the model can be enhanced by calibrating with the on-site measurements. The on-site temperature and humidity recordings in this study also helped in gaining insight into the thermal simulation result, specifically on the interpretation of the simulated Fanger's PMV values.

Subsequently, the as-built condition was simulated and the performance was evaluated with the thermal simulation results. The results indicated overheating occurs excessively in certain rooms and this verifies with one of the major findings identified from the survey, where 38.5% of the respondents indicated that they experience overheating during winter heating months. Although the survey was able to identify potential deficiencies of current systems, it was based on occupants' opinions, which are by nature subjective. The thermal simulation model was able to provide a quantitative and a more objective evaluation of the existing system's deficiency. Additionally, the simulation performed on the existing single-detached house evaluated the potential benefits multi-zone system can bring to the dwelling and simulation results show that the multi-zone system can potentially mitigate the systemic problem with the heating systems utilized in low-rise residential buildings built today.

This study was based on as-built conditions of one existing house, and future research can focus on the impact of varying parameters, such as orientation, massing, and structure, on the thermal and energy performances. This research also disregards the potential improvements of replacing the single-stage furnace with higher-efficiency central plant equipments and is subjected to further studies.

Thermal sensation profiles were established for the indoor environment, but it is important to note that the thermal comfort levels simulated in this study considered the steady-state condition and did not consider the thermal environment where parameters change dynamically. Further work needs to be carried out to incorporate transient indoor environmental conditions into thermal simulation programs.

5. Conclusions

This thesis reviewed the application of thermal simulation during the schematic design and post-occupancy phases and showed the potential benefits in integrating thermal simulation studies in each of these phases. The use of such programs facilitates better understanding of the design problem and help evaluate design solutions with regards to both thermal and energy performances. Historically, thermal simulation programs are predominantly used by research groups or academia due to their complexity and excessive input requirements, the required time and monetary investments to educate building designers in using these programs, and the lengthy simulation times. However, the use of thermal simulation is expected to increase gradually due to drastic improvements in computing power, simpler simulation program interfaces, changes of perception of the usability of these programs, and most importantly, the need to evaluate building performances due to new emphasis on and increased demand for low-energy buildings.

The conventional building design delivery process lacks opportunities to explore energy conserving design strategies. Buildings are usually designed and constructed without being subjected to comprehensive energy analyses. The energy performance of buildings is dependent on complex interactions between the different building systems and the environmental factors that the building is subjected to. To provide substantial improvements in energy consumption, thermal simulation programs can be used to predict the performances of different energy conserving design strategies. The thermal simulation model acts as a feedback tool, where results generated can provide critical information in help recognizing energy conserving strategies that can be incorporated into the final building design. These strategies might be otherwise disregarded had the study not been undertaken.

Generally, buildings are not subjected to comprehensive evaluations after they are built. As a result, buildings are inhabited and operated without consideration of strategies that could, in many cases, help improve the overall performance. Buildings might not be constructed to standards, and conducting thermal simulation studies with as-built conditions can help highlighting poor performances in existing buildings. For evaluating performances of existing buildings, gathering feedback from occupants is an imperative step. It is essential to gain insight into deficiencies of the existing system before mitigation strategies can be suggested.

Simulation study can then evaluate the performances of alternatives and identify features that can potentially resolve the problem identified.

This thesis illustrates that the usage of thermal simulation programs in various phases of buildings' life-cycles can help identify strategies that are effective, less effective, or even counter-effective in achieving high performance designs. Results from thermal simulated studies would not only improve the energy efficiency of subjected buildings, but would also provide design professionals with the knowledge necessary to change their accepted standard practices for future building designs.

New government legislation is a strong driving-force behind the push for the building industry to build more energy-efficient buildings. Currently, there exists government program that promotes the use of thermal simulation in building designs. For instance, the Better Building Partnership program sponsored by the City of Toronto provides monetary incentives for building projects that utilize thermal simulation in evaluating energy conserving strategies. Additionally, many municipal buildings across Canada are beginning to adopt LEED as design framework or building standard. With up to 20% of total achievable LEED points dedicated to demonstrating energy efficient design using thermal simulations, maximizing LEED points obtained from using thermal simulation is essential to achieve higher LEED rating. Major cities such as Vancouver, Richmond, Victoria, Edmonton, and Kitchener have committed or adopted policy to build LEED standard municipal facilities. With the ever increasing demand for more energy-efficient buildings and strong political push from the government, the use of thermal simulations in help generating more energy efficient design solutions will soon become a common practice, or even a requirement.

5.1 Future work

This thesis focused on predicting building performances with thermal simulation programs. This study can elaborate on the potential of incorporating other simulation programs into buildings' life-cycles. Simulation programs such as those focuses on day-lighting, renewable energy systems, and life-cycle environmental costs are gaining popularity and the impact these programs can bring to the overall building performance should be studied in further details.

While conducting thermal simulations are essential in generating an energy-efficient design, it is important to note that however, building design is a multi-faceted task. Strategies that maximize energy performances can work in favour or against other performance indicators such as those related to day-lighting potential, durability of building systems, and IEQ, etc. Sensitivity analysis should be applied over the predicted energy performances in order to evaluate associated impacts energy conserving strategies could have on other performance indicators.

Whenever possible, thermal simulations should be coupled with other simulation programs such as those that can optimize day-lighting, mechanical systems, and potential of natural ventilation, etc. to generate a more holistic view on the potential energy performances of building designs. Research and development on design programs that can incorporate the various aspects of building performances should be explored.

Appendix A - Blank copy of the occupant survey

Ontario Residential House Heating Ventilation and air conditioning (HVAC) Survey

The set of questions below was approved by the local ethics review board.

Entry Section

Q1. Is this dwelling owned by a member of this household?
Ans. Yes / No / Don't know
Q2. Number of occupants
Q3. On an average weekday is there someone at home all day?
Q4. Household total income per annum *Participants can choose not to answer this question
Ans. $CDN 30,000-50000 / $CDN 50,000-70,000 / $CDN 70,000-100,000 / $CDN 100,000+
Q5. Annual consumption of gas? (m^3)
Q6. Annual expenditure on gas? ($CDN)
Q7. Annual consumption of electricity? (kwh)
Q8. Annual expenditure on electricity? ($CDN)
Q9. Type of the dwelling
Ans. Single detached / Double/ row houses/Low-rise apartments/ Mobile houses
Q10. Year of construction of the dwelling?
Q11. Number of stories?
Q12. Heated area of the dwelling (Total floor space of a dwelling excluding garage)?

Thermal satisfaction

Q13. How satisfied are you with room temperature in winter?
Ans. Very dissatisfied/Dissatisfied/Neutral/Satisfied/Very satisfied
Q14. What do you tend to do when you feel thermally uncomfortable (cold) in winter? (Please circle the most predominant action)
Ans. Put more clothes on / Adjust thermostat / Use supplementary heating equipment / No action/tolerates / Gets in contact with person in charge (e.g. home owner) / Do exercise
Q15. How well do you feel you can personally control room temperature in winter?
Ans. Very badly / Badly / Neutral / Well / Very well
Q16. During winter time, do you experience overheating in certain locations of your dwelling?
Ans. Several times a day / Daily / Weekly / Monthly / Less frequently / Never
Q17. When experiencing overheating, how often would you then open the windows for better air circulation?
Ans. Several times a day / Daily / Weekly / Monthly / Less frequently / Never
Q18. During summer time, do you experience overcooling in certain locations of your dwelling? If you don't have air conditioner at home, you can leave the next 3 questions blank.
Ans. Yes / No / Don't have air conditioner
Q19. If your answer to the previous question is "Yes", how often would you then open the windows for better air circulation?
Ans. Several times a day / Daily / Weekly / Monthly / Less frequently / Never
Q20. During the summer when the air conditioner is turned on, would you open the windows for more air circulation or a fresh breeze?
Ans. Yes / No
Q21. If your answer to the previous question is "Yes", how frequently would you open the windows for more air circulation?
Ans. Several times a day / Daily / Weekly / Monthly / Less frequently / Never

Heating

Q22. What type of heating equipment provides most of the heat for the dwelling?
Ans. Furnace with forced air / Hydronic System / Electric baseboards / Heating stove/ Electric radiant heating / Others – please specify / Don't know

Q23. Average age of the heating system?
Ans. 3 years old or less / 4-5 years / 6-10 years / 11-15 years / 16-20 years / 21-25 years / 26 or more years / Not Sure

Q24. Which months the heating system is operated for?

Q25. In addition to furnace / main heating system, did your household use any other supplementary heating equipment?

Q26. What type of supplementary heating equipment did you use most often?
Ans. Electric baseboards/ Portable electric heater/ Wood stove/ Furnace /Other - specify

Q27. How many programmable thermostats do you have in your dwelling?

Q28. Set-point temperature in winter- Morning (e.g. 6a.m. to 10a.m.)

Q29. Set-point temperature in winter - During the day or not at home (e.g. 10a.m. to 5p.m.)

Q30. Set-point temperature in winter - After work/school or at home (e.g. 5p.m. to 11p.m.)

Q31. Set-point temperature in winter - Bedtime (e.g. 11p.m. to 6a.m.)

Q32. Setback when not at home?

Q33. Setback during sleeping hours?

Q34. How often do you use your thermostat to regulate temperature in your dwelling in winter?
Ans. Several times a day / Daily / Weekly / Monthly / Less frequently / Never

Q35. When was the last time your heating system is checked and maintained by a certified technician?

Q36. How often do you check or maintain your heating system by a certified technician?

Q37. Time spent in each part of the house?

a) Kitchen
b) Living Room
c) Bedroom
d) Dining Room
e) Basement (if any)

Window opening behaviour

Q38. On an average weekday, would you open your window blinds or shades and let the sun shine in for illumination when you are at home?

Q39. If your answer to the previous question is "Yes", how much time on average do you rely on the natural sunlight for illumination? If you answer "No", you can skip to the next question.

Q.40 What is the most predominant usage of your windows? Rank from 1 to 3, with 1 being the most predominant
Ans. Ventilation / Visual connection to the outside / Natural day-lighting

Appendix B - Simulation files – as included in CD-Rom provided alongside with thesis

Folder “Chapter 3” includes:

DesignBuilder file

- Chapter4Apartment.dsb : geometric detail input to EnergyPlus

EnergyPlus file:

- AT 0.1.idf
- AT 0.2.idf
- AT 0.3.idf
- AT 0.4.idf
- Basecase.idf
- Blinds0Degrees_automatic.idf
- Blinds30Degrees_automatic.idf
- Blinds45Degrees_automatic.idf
- Blinds60Degrees_automatic.idf
- Blinds0Degrees_manual.idf
- Blinds30Degrees_ manual.idf
- Blinds45Degrees_ manual.idf
- Blinds60Degrees_ manual.idf
- EPS25.idf
- EPS50.idf
- EPS75.idf
- EPS100.idf
- EPS125.idf
- EPS150.idf
- EPS175.idf
- EPS200.idf
- EPS225.idf
- EPS250.idf
- ExteriorInsulation25.idf
- ExteriorInsulation75.idf
- ExteriorInsulation125.idf
- ExteriorInsulation175.idf
- ExteriorInsulation225.idf
- InteriorInsulation25.idf
- InteriorInsulation75.idf
- InteriorInsulation125.idf
- InteriorInsulation175.idf
- InteriorInsulation225.idf
- ICF 25-200-75.idf
- ICF 50-200-50.idf

- ICF 62.5-200-62.5.idf
- ICF 75-200-25.idf
- Isokorb.idf
- Overhang0.idf
- Overhang0.5.idf
- Overhang1.idf
- Overhang1.5.idf
- Overhang2.idf
- SolarAbs0.25.idf
- SolarAbs0.45.idf
- SolarAbs0.75.idf
- SolarAbs0.875.idf
- WindowConfig1.idf
- WindowConfig2.idf
- WindowConfig3.idf
- WindowConfig4.idf
- WindowConfig5.idf
- WindowConfig6.idf

Folder “Chapter 4” includes:

DesignBuilder file

- Chapter4House.dsb: geometric detail input to EnergyPlus

EnergyPlus file:

- Basecase_19SP.idf
- Singlezone.idf
- Multizone.idf

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