An Integrated Design and Control Strategy for Energy Efficient Buildings

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An Integrated Design and Control Strategies for Energy Efficient Buildings

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(Abstract)

This research proposes a holistic evaluation model that assists architects and designers in producing buildings with low energy consumption. The model is based on computer-designer interaction. Here, the designer suggests a range of design alternatives, and, in turn, the computer evaluation model generates a matrix of design solutions and performs various environmental simulations. The performances of the various design solutions are then analyzed to derive relationships, which explain the impact that the different building components have on energy consumption. The relationships are represented in the form of statistical relations and interactive data charts.

The evaluation model was tested and used to support new ventilation strategies for the Beliveau House in Blacksburg, Virginia. The designer of this house implemented strategies for integrating solar radiation, thermal mass, thermal insulation, and air ventilation to conserve energy. A field study and computer simulation were conducted to monitor the actual performance of the house and to validate the evaluation model results.

Based on the evaluation model results, this research suggests new direct and indirect ventilation control strategies to reduce sensible and latent cooling load to improve comfort. The research also suggests general design guidelines to improve the energy performance of buildings and to enhance thermal comfort. These design guidelines are based on a holistic view of integrating the building components that has significant impact on buildings thermal performance.

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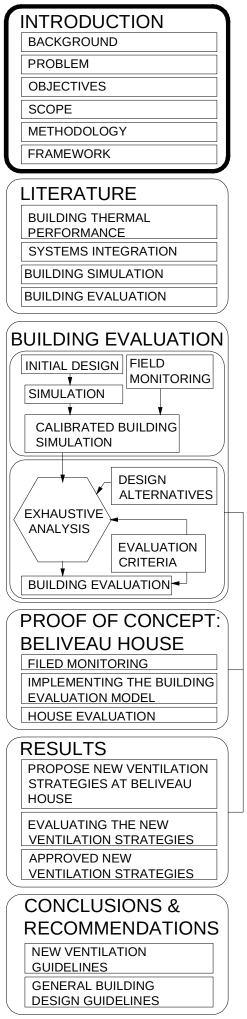
Chapter One

I : INTRODUCTION



I: Introduction

1-1 Background;

Environmental comfort, economy, and energy conservation are among the major functional considerations in buildings. The most important elements that contribute to heating and cooling loads reduction in buildings are the proper size and orientation of the solar apertures, amount of thermal insulation, and the amount and placement of the thermal storage mass within the living space (DOE 2.1, 1997). Optimizing the air-conditioning and electrical lighting operation also have the potential to significantly lower energy consumption.

Many studies have been concluded to predict the contribution of each of these elements to energy conservation (ASHRAE, 1987). The past research has resulted in general rules and design guidelines, which are intended to improve building energy performance in standard building designs. Field experiments and computer simulations were also used to determine and predict building performance, define preferred building design solutions, and suggest new building design alternatives. The goal of much of this work was to help the designer include energy conservation as an objective.

However, the complexity of this subject makes general rules broad and relatively inaccurate. Furthermore, they do not allow for the integration of other design elements such as shading devices and operating strategies like natural ventilation or nighttime ventilation, which also contribute to energy conservation.

In addition, many simulation programs have been developed to estimate energy performance. Some of these simulation programs compare the simulated building performance to a “standard design” (Malkawi,1994), and provides a comparison between the two designs. Other software programs run multi-simulations for simple building geometries and derive an “optimum” building design from an energy conservation point of view (Al-Homoud, 1994). However, this software falls short of deriving the actual interaction between building design variables. Nor does it reveal the contribution of each energy saving element for specific buildings.

Air-conditioning control can reduce change the total air-conditioning energy consumption in buildings by up to 47% if it is integrated with the other building design variables such as thermal mass (Mahdavi, 1995). Advances in air-conditioning system design and control strategies are among the major contributors to energy savings in existing buildings, which can reach up to 38% when compared to conventional approaches (Osman, 1996). This high saving potential has captured the attention of engineers. Related research topics include: development of a systems approach to optimal air-conditioning control, application of general regression neural networks in air-conditioning control, fuzzy logic and rough sets controller for air-conditioning systems (Yao,T. 1996), and finally, non-linear air-conditioning control (Zaheer, 1994). These studies introduced innovative solutions to control the air-conditioning systems and to improve the comfort level in buildings. However, none of these investigations integrate the impact of building components on thermal performance in a holistic way.

1-2 Problem statement;

Thermal comfort is a basic need for human beings. It is imperative to consider thermal quality in building design. Because of the mathematical nature of evaluating thermal comfort in buildings, most architects tend to avoid embracing thermal design problems. Issues of thermal evaluation regarding energy minimization are typically not fully considered during the design process. Energy minimization relies on the thorough understanding of building thermal behaviour, which depends on the interaction of building elements with outside and inside variable conditions. The understanding of such interactions is based on the interpretation of complex simulation figures that rely on the nature of thermal loads and building configuration.

Early in the design phase, designers rely either on general thermal design guidelines or revert to intuitive methods that help when formulating their concept. This rarely leads to optimal energy efficient solutions. Later in the design process, the number of design parameters, constraint, and details increase. This design process affect the overall energy efficiency, and it is difficult to predict the thermal performance of the building and optimize design. As designers use rational means to select the best design alternative for energy conservation, they follow a planned sequence of steps and cycles until the objectives are met (Zmeureanu, 1992).

Due to the large number of variables considered in the analysis of several alternatives, computer assistance is essential to achieve minimum energy conservation . Computers are able to engage in repetitive cycles of thermal analysis. In addition, computers have encouraged experimentation of alternative approaches to form material and construction detailing while examining many solutions and preconditions.

This dissertation is a step towards raising awareness and provides a tool that helps designers to better understand energy conservation and systems interactions during early phase of design development. This research will also develop an evaluation model that provides computer-designer interaction. Through this research, a designer will be able to make decisions with clear understanding of the holistic performance of the building, and derives the relations which explain the contribution of the different building components to energy saving.

To demonstrate the evaluation model, this research introduces a new methodology for air ventilation. The evaluation model revealed the interaction between the major building elements, which contribute to energy consumption. The proposed air ventilation design and control is based on the outcome of the evaluation model, where the designer draws the air ventilation strategies based on the actual contribution of the different building elements in supporting the new air ventilation system.

1-3 Scope of Research;

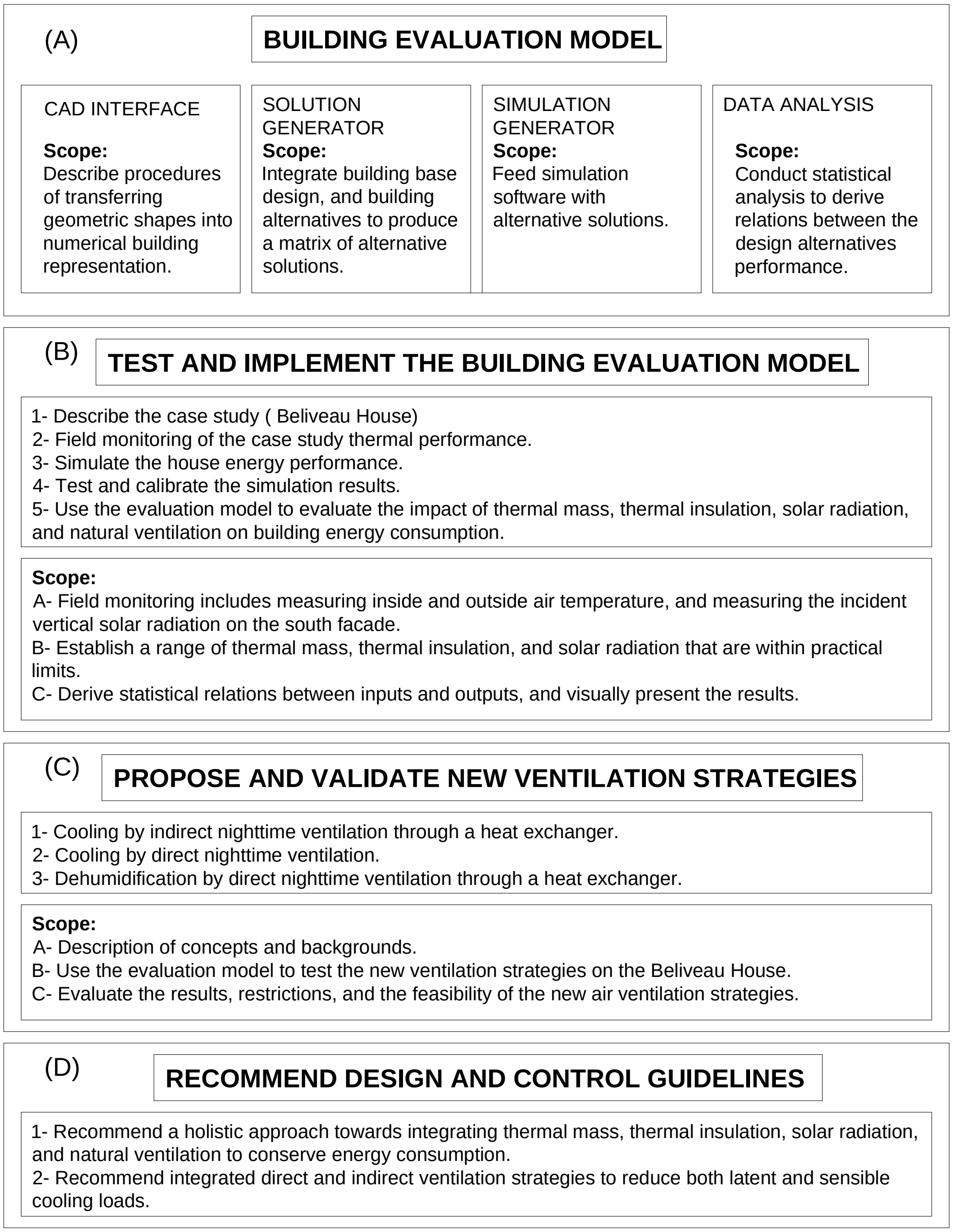
Through data collection, analysis, simulation, and evaluation, this research provides a holistic building design and control strategy to enhance building performance. This research involves proposing a building evaluation model, testing and implementing this evaluation model. Then, using the evaluation model results to propose and validate new ventilation strategies. The evaluation model was used again to validate the suggested ventilation strategies and recommend new design and control guidelines. Figure 1-1 shows the scope of this research which can be summarized as follows;

The proposed building evaluation model is composed of four major components. The first component is CAD interface that transfer the building geometry to the energy simulation software. Second, a solution generator which integrates the energy simulation input of the building base design and building components alternatives, which are the subjects of the evaluation. The solution generator output is a matrix of complete design alternative. Third, a simulation generator feeds energy simulation software with the matrix of the alternative solution to simulate them and export their results to the fourth component which is a data analysis generator. The data analysis generator conducts the analysis to derive relations between the design alternatives and their effect on energy consumption and comfort (Figure 1-1(A)).

The research also involves testing and implementation of the building evaluation model. The Beliveau House was used as a case study to test the evaluation model. The designer of this house implemented several new energy conservation strategies. The Beliveau House was field monitored to calibrate the building energy simulation. This field monitoring includes measuring the indoor and outdoor air temperature, and measuring the outdoor solar radiation and air speed. A range of thermal mass, thermal insulation, solar radiation, and ventilation was established at the Beliveau House in order to test their effect on energy consumption. The building evaluation model was used to derive statistical relations between thermal mass, thermal insulation, solar radiation, and natural ventilation on the Beliveau's House energy consumption (figure 1-1(B)).

Based on the above evaluation results of the Beliveau House, this research proposed and validated new ventilation strategies. These ventilation strategies include cooling by indirect nighttime ventilation through heat exchanger, cooling by direct nighttime ventilation, and dehumidification by direct nighttime ventilation through heat exchanger (Figure 1-1(C)).

Finally the research recommended a holistic approach towards integrating thermal mass, thermal insulation, solar radiation, and natural ventilation to conserve energy consumption. The research also recommend new strategies of integrating direct and indirect ventilation to reduce both latent and sensible cooling load (Figure1-1(D)).



(A) **BUILDING EVALUATION MODEL**

CAD INTERFACE

Scope:
Describe procedures of transferring geometric shapes into numerical building representation.

SOLUTION GENERATOR

Scope:
Integrate building base design, and building alternatives to produce a matrix of alternative solutions.

SIMULATION GENERATOR

Scope:
Feed simulation software with alternative solutions.

DATA ANALYSIS

Scope:
Conduct statistical analysis to derive relations between the design alternatives performance.

(B) **TEST AND IMPLEMENT THE BUILDING EVALUATION MODEL**

1- Describe the case study (Beliveau House)
2- Field monitoring of the case study thermal performance.
3- Simulate the house energy performance.
4- Test and calibrate the simulation results.
5- Use the evaluation model to evaluate the impact of thermal mass, thermal insulation, solar radiation, and natural ventilation on building energy consumption.

Scope:
A- Field monitoring includes measuring inside and outside air temperature, and measuring the incident vertical solar radiation on the south facade.
B- Establish a range of thermal mass, thermal insulation, and solar radiation that are within practical limits.
C- Derive statistical relations between inputs and outputs, and visually present the results.

(C) **PROPOSE AND VALIDATE NEW VENTILATION STRATEGIES**

1- Cooling by indirect nighttime ventilation through a heat exchanger.
2- Cooling by direct nighttime ventilation.
3- Dehumidification by direct nighttime ventilation through a heat exchanger.

Scope:
A- Description of concepts and backgrounds.
B- Use the evaluation model to test the new ventilation strategies on the Beliveau House.
C- Evaluate the results, restrictions, and the feasibility of the new air ventilation strategies.

(D) **RECOMMEND DESIGN AND CONTROL GUIDELINES**

1- Recommend a holistic approach towards integrating thermal mass, thermal insulation, solar radiation, and natural ventilation to conserve energy consumption.
2- Recommend integrated direct and indirect ventilation strategies to reduce both latent and sensible cooling loads.

Figure 1- 1: Overall research scope.

Figures 1-2 presents the scope of this research and the overall framework for a complete building evaluation model. The highlighted boxes are the focus of this research. There are many components to overall building evaluation. This research concentrates on building environment as it is shown on line 1 Figure 1-2. Within the building environment aspect, the research evaluates the building thermal performance, and addresses the building envelope and system operation (Line 3, Figure 2). For the building envelope, the research studied

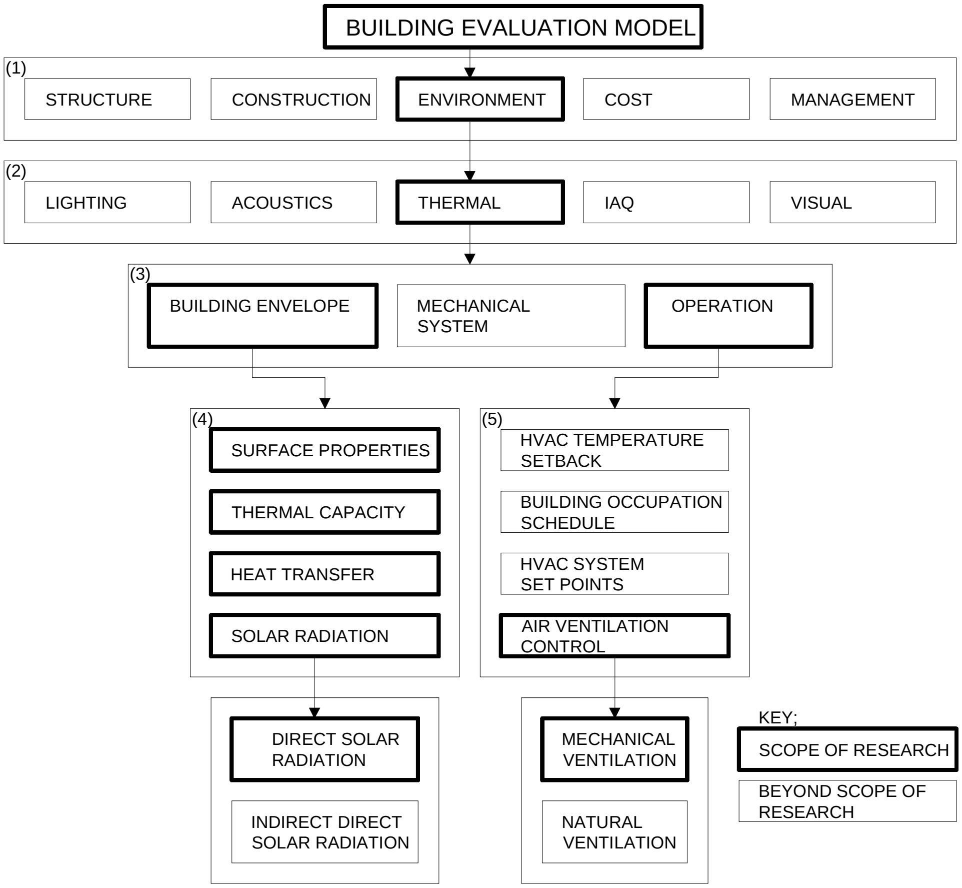


Figure 1- 2 : Location of research in the body of knowledge.

Overall Building Evaluation Framework and the scope of this research (highlighted components) the building surface properties, building materials sensible and latent thermal heat capacities, heat transfer coefficients, and direct solar radiation gain are studied (Line 4, Figure 2). The evaluation of the operation parameters includes; the direct and indirect mechanical air ventilation rate on reducing cooling loads (Line 5, Figure 2).

1-3-1 Research Objectives;

The principal objectives of this study are: to propose a framework for the prediction and holistic evaluation of building thermal performance, implement these methods by developing an evaluation model which will test, simulate, evaluate, and aid in thermal design decisions by providing a holistic picture of the actual contribution of major building design energy saving elements.

This study will use the evaluation model results to explore energy saving potential , and ways to enhance thermal quality in buildings by introducing new air ventilation strategies.

1-3-2 Research methodology;

This research involves proposing a building evaluation model which acts as a central agent between a Base Design Generator (Figure 1-3(A)), and Alternative Design Analysis Tool which consists of a solution generator, a simulation generator, and a data analysis generator (Figure 1-3 (B)). The evaluation model was used to recommend general design guidelines for using the thermal mass, thermal insulation, solar radiation, and natural ventilation (Figure 1-3(D)). In light of these recommendations, the research suggested new design and control strategies that include cooling by indirect nighttime ventilation, cooling and dehumidification by direct ventilation, and dehumidification by direct ventilation through heat exchanger (Figure 1-3(C)).

Then the evaluation model was used again to test and validate these new ventilation strategies. Finally, the research recommended general ventilation design and control guidelines for similar buildings (Figure 1-3(E)).

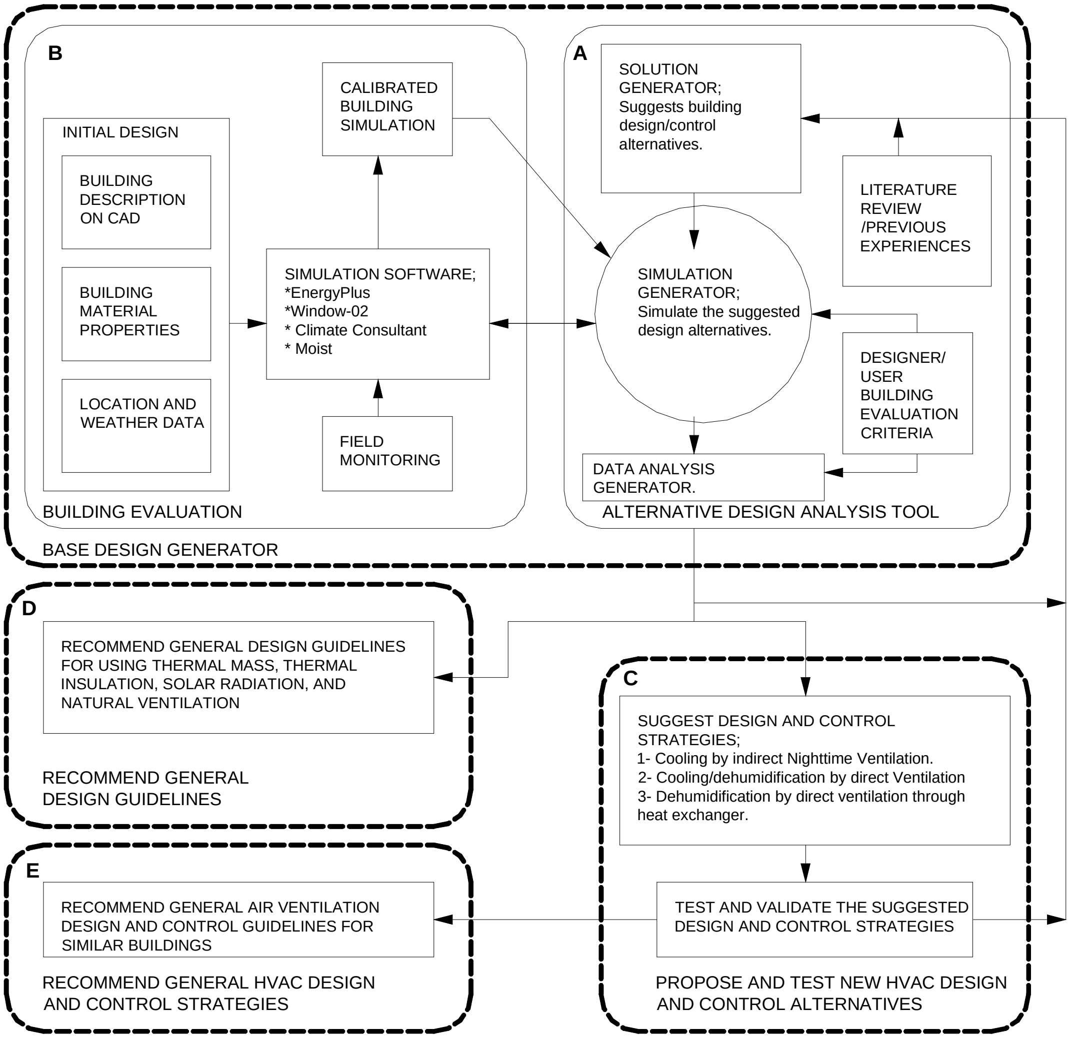


Figure 1- 3: Building evaluation structure overview.

1-3-2-1 Base Design Generator;

The base design generator generates a initial design, and simulates the initial design in energy simulation tools. If the evaluated building is exist, a filed monitoring is used to calibrate the building simulation against the field readings. These methodology is explained as follows;

1-3-2-1-1 Generating initial design;

First, building parameters are described in the EnergyPlus© software. EnergyPlus© software requires initial building data, which includes location criteria, materials properties, mechanical system components, (Figure 1-4(A)) and thermal comfort parameters. EnergyPlus© also requires daily weather data description (Figure 1-4(C)).

Then, Auto CAD 2000© is used to transfer building formation to a suitable file format, which feeds EnergyPlus© with building formation (Figure 1-4(B)). Both building configeration and building components description form the initial building design.

1-3-2-1-2 Simulating the building energy performance;

The EnergyPlus© software was used to simulate the building energy performance. EnergyPlus© was selected for its capability of simulating heat transfer through the building envelope, solar radiation heat gain, natural ventilation, building heat load, active heating and cooling, predictive mean radiant temperature, moisture transfer, and comfort parameters. EnergyPlus© is the Department of Energy (DOE) official energy simulation software, and has its roots in DOE2 and BLAST energy simulation tools (EnergyPlus©, 2001). EnergyPlus is also supported by other simulation software such as WINDOW and Climate Consultant (Figure 1-3(D)).

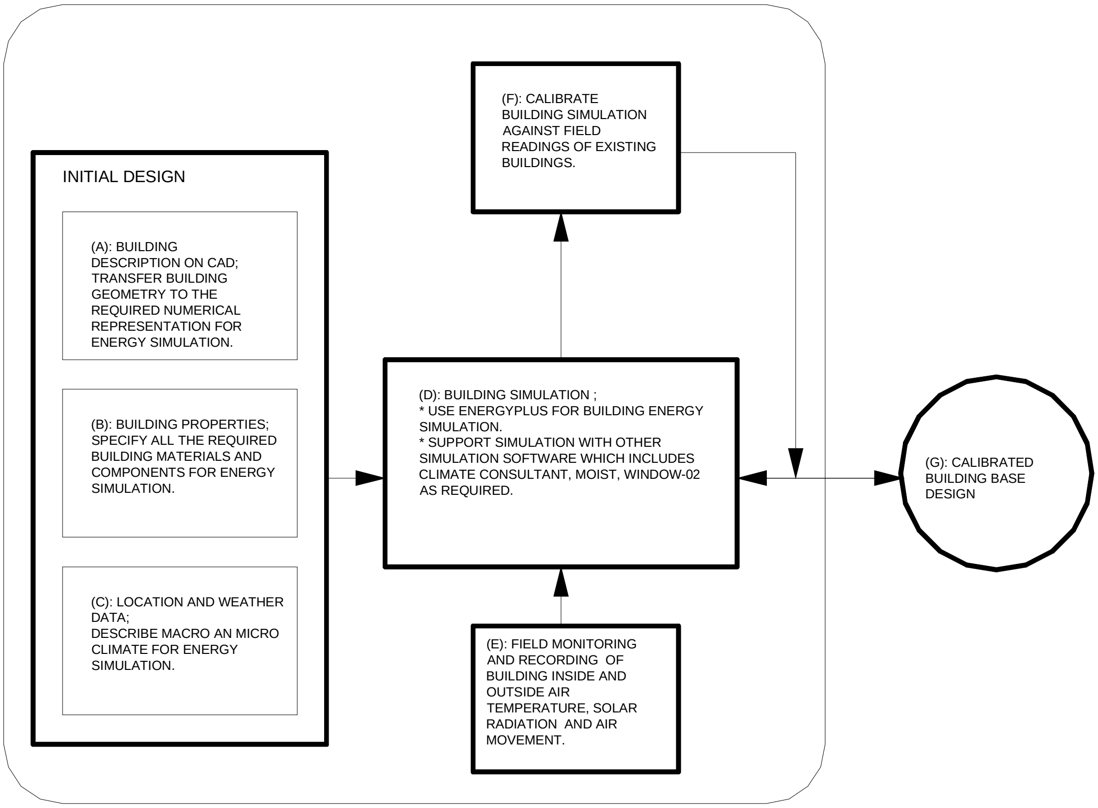


Figure 1- 4: Base design generation.

1-3-2-1-3 Field study;

A field study was carried out at the Beliveau House to calibrate the computer simulation results (Figure 1-4(E)). The field test includes installing a data acquisition system at the Beliveau House to monitor actual building performance in different weather conditions which extended from November to August. The system records air temperature, building surface temperature, solar radiation, and wind velocity in the house. The results were stored and analysed by Microsoft Excel 2000's statistical analysis tool.

1-3-2-1-4 Calibrate the simulation results;

To calibrate the building simulation, EnergyPlus© simulation results were compared to the field readings (Figure 1-4(F)).

Under passive control, the house simulation was calibrated by matching the inside air temperature of the house with the field readings, and under active thermal control, the house simulation results were calibrated with the operation of the house air-conditioning as well as matching the inside air temperature of the house with the field readings.

This calibration technique was used by DOE and ASHRAE to calibrate the simulation software before using them to derive relations between building components and the building thermal load (Ronald, 1985). Furthermore, field readings are used to fully understand the building behaviour under the different house activities, account for the intangible variables, and compensate for the variables that are not addressed by the simulation results.

1-3-2-2 Alternative Design Analysis Tool;

After establishing the base design, the designer selects building components which are required to be tested, and then establishes a matrix of ranges of these building component alternatives such as a range of wall insulation thickness, window glass properties, roof and exterior walls solar radiation absorption, natural ventilation rates, or comfort level set points (Figure 1-5(A)). The EnergyPlus© basic design file, and the alternative building component file are used to generate a matrix of complete input solutions to feed the simulation software. A simulation generator runs these design alternatives in EnergyPlus© and saves the results in appropriate file format(Figure 1-5(B))

A Visual Basic© subroutine accesses the design alternatives and their associated simulation results which are obtained by EnergyPlus©, and runs them in a statistical analysis tools to extract mathematical relationships among the building component alternatives. These relations, can also be exhibited in several charts (Figure 1-5(C)).

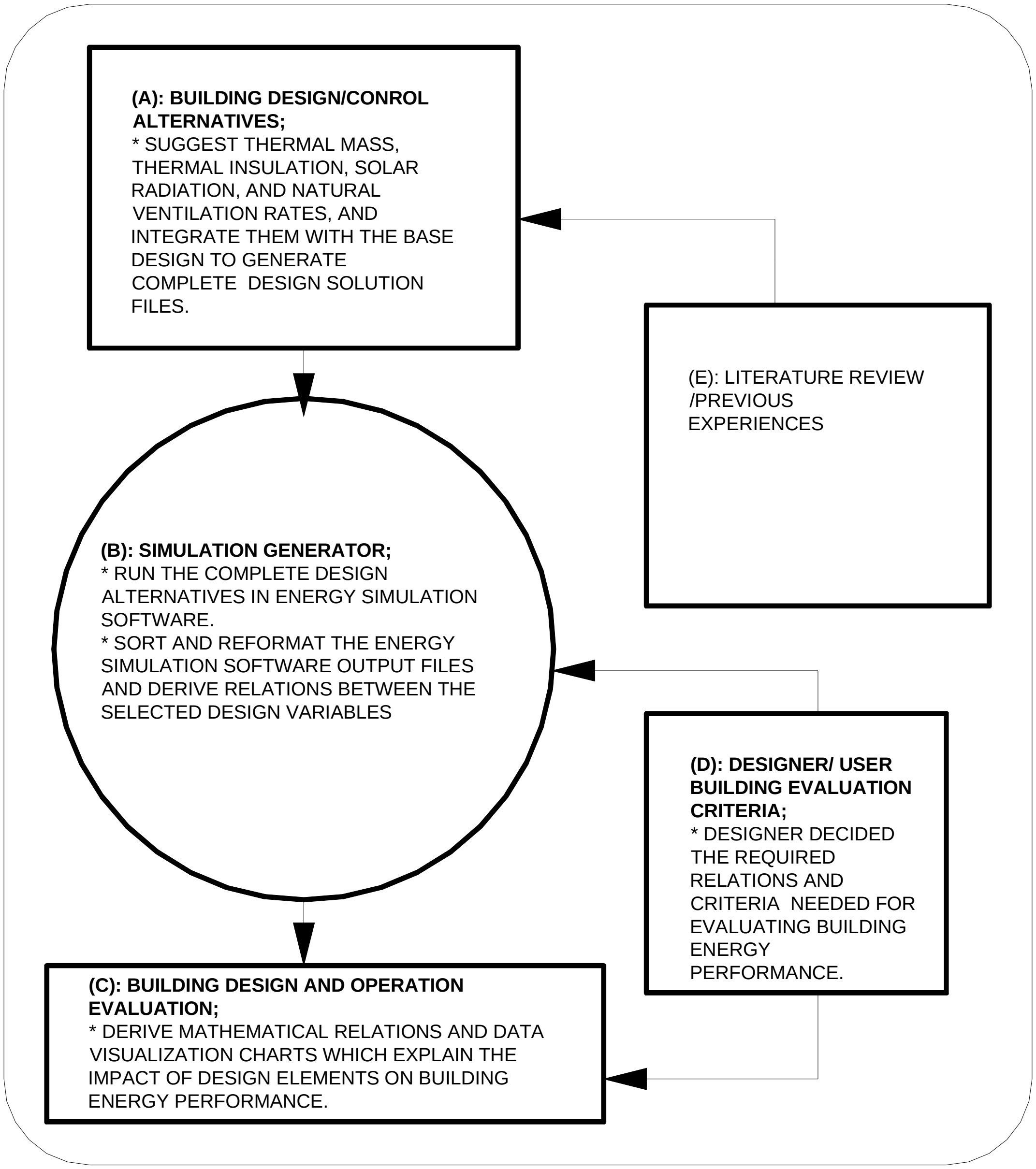


Figure 1- 5: The evaluation model building simulation and analysis engines.

1-3-2-3 Implementation of the research framework;

To validate the evaluation model, the interaction between thermal mass, thermal insulation, solar radiation, and natural ventilation were studied in the Beliveau House (Figure 1-5(D). Based on the findings of the building evaluation, this research also proposes air ventilation control strategies for residential buildings in moderate climates to reduce both sensible and latent cooling load (Figure 1-5(C)). The evaluation model was used to test and validate these control strategies.

1-3-2-4 Interpolate holistic design and control strategies;

In light of the research results, the research alludes to a holistic design and control strategy that will provide better thermal performance for similar buildings. The findings will also raise awareness about potential energy saving in buildings, while considering other design aspects, as well (figure 1-2(E)).

1-4 Contribution to the Body of Knowledge;

- This research introduces a new holistic evaluation model to predict and evaluate building thermal performance. The evaluation model will test, simulate, evaluate, and aid in thermal design decisions by providing a holistic picture of the actual contribution of major building design energy saving elements.
- The evaluation model was used to derive air ventilation strategies, which integrated direct ventilation, indirect ventilation, and direct ventilation through heat exchanger to reduce both latent and sensible cooling load.
- The research proposes new strategy to integrate the latent building thermal storage with air ventilation to reduce latent thermal load.

1-5 Research limitations;

Since the research involves multi-disciplinary subjects and field study, there are limitations and restrictions raised through the research. These are presented in 1-5-1, and 1-5-2 below.

1-5-1 Technical limitations;

A field study was conducted for the Beliveau House: The collected data was used to give a comprehensive picture of the house's performance. However the available data acquisition instrument used had only 8 input channels, which limits the number of thermocouples installed in the house to measure the different surface temperatures. The data acquisition system was installed in the house for six months during both cold and hot periods. Two readings were recorded at each input channel.

Although EnergyPlus© was thoroughly tested and calibrated, some technical limitations arose while using this software, which required co-operation between the researcher and EnergyPlus© help support to overcome these difficulties, These difficulties will be discussed later in chapter four and five.

1-5-2 Time limitations;

The field study was carried out during different climate conditions, which extended from November to August. Since Beliveau House was occupied, it was difficult to keep the wires and instruments in the house for long periods, or to remove and then re-install the data acquisition system. Although the monitoring time was limited, enough data were collected for successful calibration of the energy simulation software.

1-6 Organization of dissertation;

The dissertation is presented in six chapters covering background information and the problem statement, literature review, development of the evaluation model, field test, implementation of the evaluation model to predict energy conservation at Beliveau House, and propose and test through the evaluation model new air ventilation strategies, and finally, the conclusions and recommendations.

Chapter One: Introduction;

Chapter One gives background information, presents the problem statement and the primary and secondary objectives, discusses the research methodology, as well as the scope and limitations of the research. This chapter also highlights the contribution to the body of knowledge in energy conservation.

Chapter Two: Literature Review;

Chapter two reviews the basic principles of building thermal behaviour, the available research on systems integration for conserving energy in buildings, the contribution of the major building components to energy savings and techniques for utilizing statistical analysis in energy conservation studies. This chapter also addresses the applications, scope, and limitations of computer simulation for energy conservation, validating the simulation results against field studies, and air-conditioning system operation strategies and techniques.

Chapter Three: Energy conservation Evaluation Model;

Chapter three discusses the concept, components and procedures involved in a holistic building evaluation model. It describes developing an AutoCAD interface, which extracts building formation from CAD drawings, creates a solution generator, which prepares design alternatives for a given building, and runs these solutions in the simulation software. This chapter also discusses the means and methods used to extract statistical relations generated from the simulation results.

Chapter Four: Proof of concept;

Chapter four discusses the field study, which is used to analyze the performance of Beliveau house and to calibrate the simulation results, use of the evaluation model to explore the contribution of controlled solar radiation, thermal insulation, and mechanical air ventilation to energy saving, and finally derive a holistic view of building energy performance.

Chapter Five: Implementation of evaluation model;

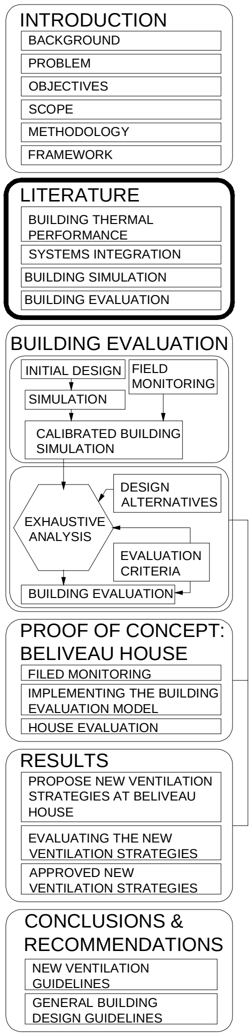
Chapter five describes the methodology for integrating the proposed evaluation model to derive new natural ventilation operation strategies for Beliveau House. These approaches to natural ventilation include; the concepts and the theories behind the new ventilation strategies, the anticipating energy saving, the anticipated indoor air quality enhancement , and the restrictions and precautions which must be considered in applying these ventilation strategies.

Chapter Six: Conclusions and Recommendations;

Chapter six summarizes the research results, and presents general design guidelines for integrating thermal mass, thermal insulation, and solar radiation to save energy in buildings. It also recommends new natural ventilation strategies, and suggests future research that may build on the outcome of this study.

Chapter Two

II: LITERATURE REVIEW



II. Literature Review;

The development of a holistic building evaluation model must begin with an understanding of the factors, which influence energy consumption. This chapter reviews the basic principle of building thermal behaviour, the available research on systems integration for conserving energy in buildings, the contribution of the major building components to energy saving, and utilizes statistical analysis in energy conservation studies. This chapter also addresses the potentials, scope, and limitations of computer simulation for energy conservation, validating the simulation results against field studies, and air-conditioning system operation strategies and techniques.

2-1 Thermal performance of Buildings;

This research address the most important factors that determines energy consumption in buildings, which are solar radiation, thermal mass, thermal insulation, air ventilation, and HVAC control systems, as well as thermal comfort. The following is a brief theoretical description of the effect of these elements on energy consumption.

2-1-1 Indirect and Direct Solar Gain;

Solar radiation refers to the infrared wavelengths of the electromagnetic spectrum ranging from 0.7 to 100μm. The wavelength spectrum of the radiation emitted by a body depends on its temperature. In radiant heat transfer, the rate of heat flow depends on the temperatures of the radiating and receiving surfaces and on the surface qualities absorbance ($\propto$) and emittance (ε).

The density of radiant emission (E) in Watt per m² (W/m^2) is

$$E = 5.67\varepsilon\left[\frac{T}{100}\right]^4 \qquad \text{Eq. \#2-1}$$

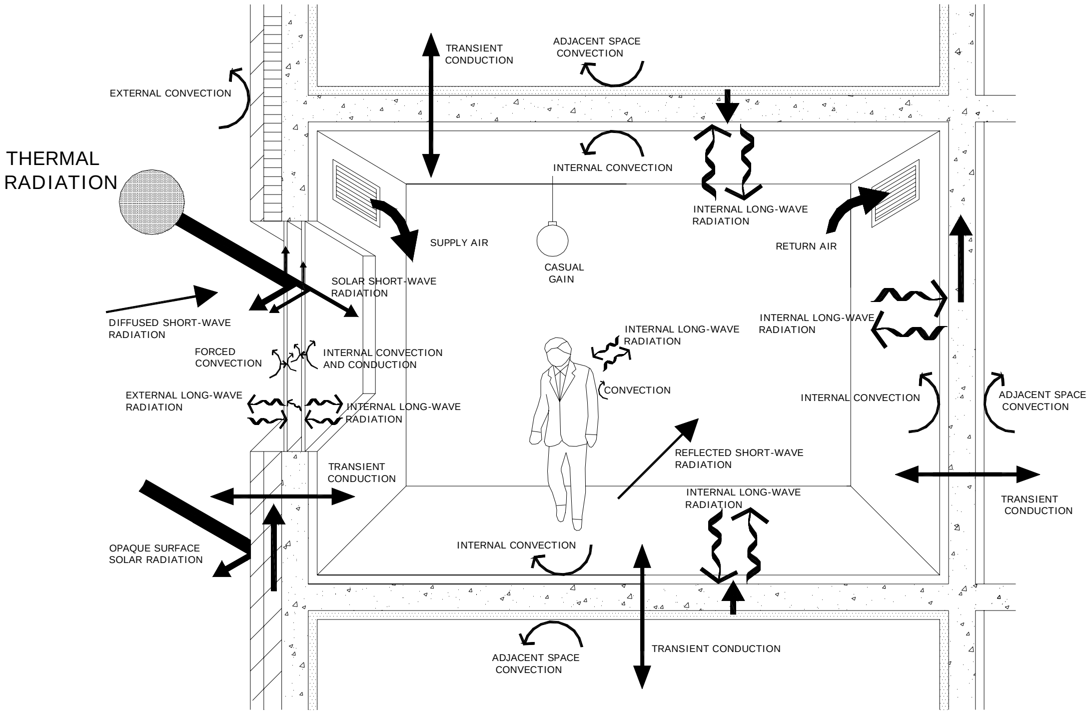


Figure 2- 1: Heat transfer and thermal energy balance in a space.

The heat flow due to radiation *E* (in Watts) may be expressed by

$$E = 5.67\varepsilon A\left[\frac{T}{100}\right]^4 \qquad \text{Eq. \#2-2}$$

or between two opposed surfaces, equal and parallel as:

$$E = 5.67\varepsilon A\left[\left(\frac{T^1}{100}\right)^4 - \left(\frac{T^2}{100}\right)^4\right] \qquad \text{Eq. \#2-3}$$

Where T = absolute temperature of the body (°K), and surface area (A).

The emittance (ε), and absorbance (α) of a surface vary with wavelength. For example, a matt black body emittance is equal to its absorbance which is 0.96, while aluminium (oxidized) absorbance is 0.2 and its emittance is 0.11 (Szokolay, 1980). If the incident radiant flux density (G) is known, the heat absorbed by the surface (Q_r) will be

$$Q_r = A \times G \times \alpha. \qquad \text{Eq. \#2-4}$$

2-1-1-1- Indirect Solar Radiation Gain;

Indirect solar radiation gain refers to the heat gain due to solar radiation that is absorbed by the building envelope and transferred to the building by conduction, convection or infra-red radiation (Stein, 1991). In the analysis of heat transfer from air into a body such as a wall, or vice versa, usually both radiant (h_r) and convective (h_c) components are combined into a single surface conductance term (f):

$f = h_r + h_c$ W/m² degC.

$$Q_{loss} = A \times f \times d_t \qquad \text{Eq. \#2-5}$$

Where d_t is the difference between the temperature of the surface (t_s) and the environment $(t_\circ)$, which is $(t_s - t_\circ)$. With continued radiation input, the surface temperature will increase. Consequently, the heat loss from the surface will also increase until equilibrium is reached when the rate of this heat loss equals the radiant heat input. Thus the thermal balance equation will be:

$$A \times G \times \alpha = A \times f \times (t_s - t_\circ) \qquad \text{Eq. \#2-6}$$

And if $t_\circ$ is known,

$$t_s = t_\circ + \frac{G \times \alpha}{f} \qquad \text{Eq. \#2-7}$$

Since this equation neglects any heat flow through the surface, t_s will not be a true surface temperature, and it is referred to as the sol-air temperature. Sol-air temperature is defined as the temperature of the outdoor air which, in the absence of all radiation exchanges, would give the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, and radiant energy exchange with the outdoor air (ASHRAE, 2001) Sol-air temperature represents the driving force of heat flow into a building when the outside surface is exposed to solar radiation, and is used in the conduction heat flow expression

$$Q_c = A \times U \times \Delta t \qquad \text{Eq. \#2-8}$$

by taking $\Delta t = t_s - t_i$

Where t_i = the indoor air temperature.

Unlike convective heat gain, which is instantaneously converted to cooling loads, radiative heat gain is absorbed by building surfaces and thus delayed before impacting the cooling loads. To predict the heat storage delay due to solar radiation gain, the Transfer Function Method (TFM) is often used to quantify the heat absorbing characteristics of a particular building and predicts its heat storage delay action performance (EnergyPlus, 2001). Transfer functions are based on two concepts, the conduction transfer factors (CTF) and the weighting factor (WF). The CTF are used to describe the heat flux at the inside wall, roof, partition, ceiling, or floor as a function of previous values of the heat flux and previous values of inside and outside temperature. The WF is used to translate the zone heat gain into a cooling load. ASHRAE used the (TFM) to compute the one-dimensional transient heat flow through various sunlit roofs and walls. The heat gain was converted to cooling load. The results were then generalized by dividing the cooling load by the U-factor for each roof or wall. The results thus obtained are in units of total equivalent Cooling Load Temperature Difference (ASHRAE, 2001). The TFM method is also used simulation software such as BEANS, BLAST, and EnergyPlus, (Malkawi, 1994), (BEANS, 1997).

In summary, indirect solar gain in buildings is a function of many design parameters. It is difficult to accurately predict the effect of indirect solar radiation on heating and cooling loads through direct relationships. Many statistical analysis approaches and simulation tools have been implemented to investigate the effect of indirect solar radiation gain in buildings. These simulation tools such as BEANS account for orientation of building surfaces, sun movement, weather conditions, as well as the building component properties (Simonds, 1991).

2-1-1-2- Direct solar gain;

Fenestration is the term used by ASHRAE to designate any light-transmitting opening in a building wall or roof (ASHRAE, 2001). When solar radiation is incident on a transparent surface, some of it will be reflected, some transmitted and some absorbed, heating the glass itself. The heated glass will re-emit the absorbed heat, both inwards and outward (Figure 2-2).

Heat admission or loss through fenestration is affected by many factors of which the following are the most significant.

- Solar radiation intensity and incident angle.
- Outdoor-indoor temperature difference.
- Velocity and direction of air flow across the exterior and interior fenestration surfaces.
- Exterior and/or interior shading.

The solar gain factor (θ) is the sum of the transmittance and the inward re-emission. It can be estimated by equation 2-9.

$$\theta = \tau + \frac{\alpha}{2} \qquad \text{Eq. \#2-9}$$

Where

τ= transmittance.

α= absorbance

The solar gain for windows Q_s is

$$Q_s = A \times G \times \theta \qquad \text{Eq. \#2-10}$$

Where A= area of window m^2

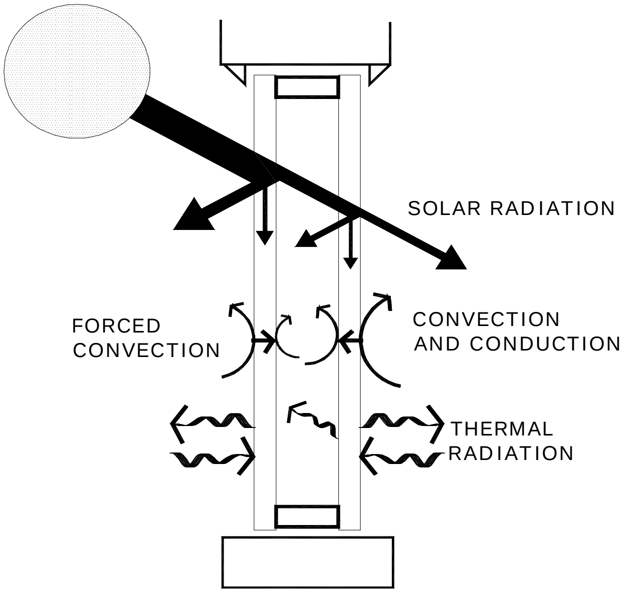


Figure 2- 2: Direct and indirect solar radiation gain at glass window.

To accurately predict the direct solar radiation gain, we should have enough information about the amount of hourly solar radiation on the building, type of solar radiation (eg. direct solar radiation beam or diffused solar radiation), orientation of glass surfaces, location and sizes of glass areas in the building, and the glass properties.

Much research has been concluded using computer simulation to predict the direct solar heat gain. Computer simulation offers designer the opportunity to employ more detailed solar radiation transfer models, as well as the ability to demonstrate a large number of glazing systems, such as low-e glass, solar-control coating, selective glass tint, substitute fill gases, and glazing layers that partially transmit long wave radiation. WINDOW-2 is a good example of these simulation models (WINDOW, 2000).

In a step further, software developed by EGYSAO determines the instantaneous solar radiation transmitted through a window and absorbed by each room’s interior surface. It also provides a correlation for estimating the fraction of daily total transmitted solar radiation absorbed by the floor at several latitudes, for different shapes and enclosures, and for varying surface solar absorption levels (EGYSAO, 1997).

In summary, it is clear that evaluating solar radiation gain in buildings is complex and interrelated with other design variables. Evaluating direct solar radiation requires powerful computer simulation tools.

2-1-2 Building thermal mass;

In hot dry and moderate climates, thermal mass is a major element in traditional architecture. Thermal mass is most beneficial when the diurnal temperature cycle is large. Traditional buildings give the best examples of integrating thermal mass with other design variables to provide comfort. Figure 2-3 shows a mud building in Nigeria; During the day, the air that passes through a wind tower losses both moisture and heat, and during the night, the heavy mud wind tower extracts excess heat and moisture by stack effect.

The amount of thermal mass in buildings is an early design question. This mass determines the building thermal storage capacity. The distribution of thermal mass is also important. In direct-gain systems, thermal mass should be within the direct-gain-heated space, and the exposed surface area of the mass should be at least three times the glazing area (Stein, 1991). Also the thickness of most thermal mass walls or floors should not be more than 100mm- 150mm. However, the desired amount and distribution of thermal mass has direct relation with the availability of solar radiation (Stein, 1991).

The thermal capacitance of a building envelope is the product of the mass per unit area (kg/m²) and the specific heat of the material (j/kg C°). This thermal capacity does not influence the heat flow through the wall under steady state conditions, so there is no capacitive insulation effect. For example, a 220 mm brick wall would allow the same rate

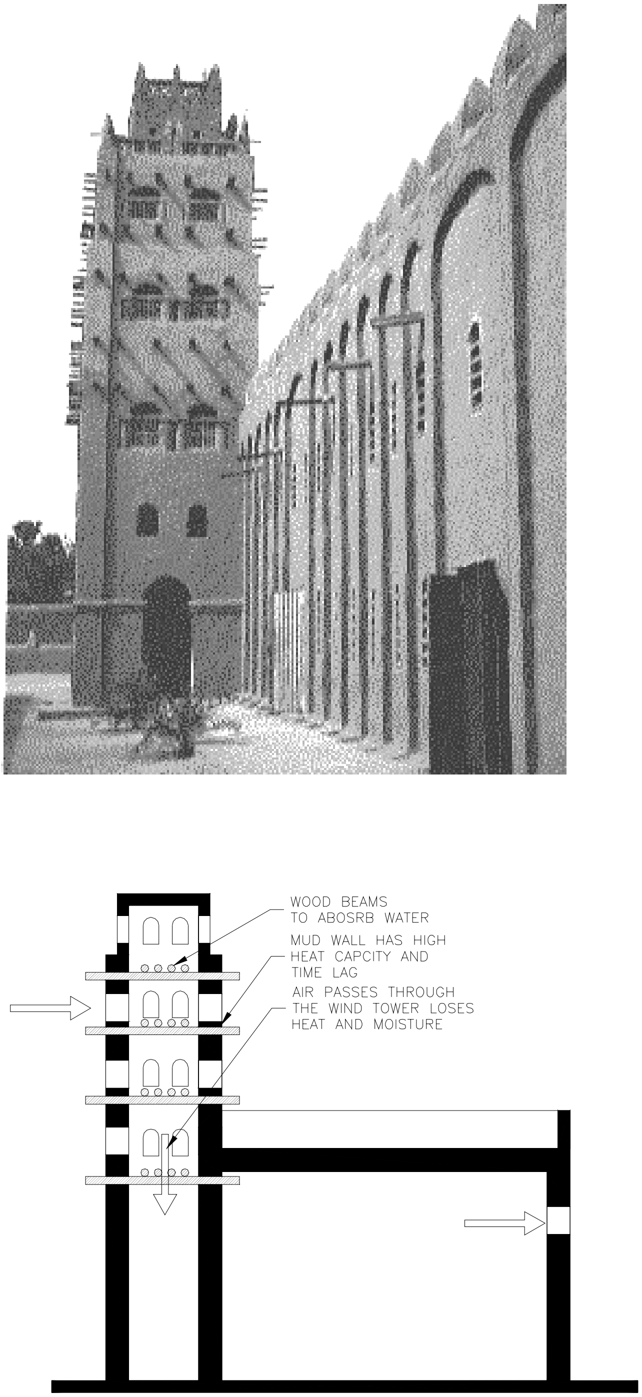


Figure 2- 3: Massive building with a wood mesh wind tower .

The upper picture shows the building from outside and the section below shows the building structure. (Picture by Mehdi, 1985).

of heat flow as an approximately 10mm thick polystyrene slab under a steady state condition. However the steady state conditions rarely exist because even if the indoor temperature is relatively constant, the outdoor temperature is always typically changing.

In a massive building element, for a unit heat input on one side, the rate of temperature increase is influenced by the material conductivity (k), density (ρ) and specific heat (c_ρ). The relationship between these factors is expressed by the term thermal diffusivity (α) which is given in equation 2-11

$$\alpha = \frac{k}{\rho \times c_p} \qquad \text{Eq. \#2-11}$$

Dimensionally:

$$\frac{w / mC^{\circ}}{kg / m^{3} \times j / kC^{\circ}} = \frac{m^{2}}{s} \qquad \text{Eq. \#2-12}$$

As we may notice from the above relation, if the material has high conductivity, the rate of temperature increase will be higher, and if the material has a high specific heat, the rate will be slower.

Much research has been conducted to maximize energy saving by using thermal mass. A simulation tool has been developed by Andersen, which characterizes the dynamic thermal performance of a typical office space in conjunction with thermal mass, heat transfer coefficients, and furniture. The simulation tool predicts the amount of energy stored in the internal building mass, and the total cooling and heating load in the offices. However, this tool is not commercially available (Anderson, 1995).

Yohanis introduced a utilization factor for building solar heat gain for use in a simplified energy model. The utilization factor, which is a function of weather and building thermal response, is determined by using data obtained from a dynamic hour-by-hour thermal analysis of solar energy absorption in a generic office building. The researcher found that this factor depends mainly on zoning and the time constant

(Yohanis, 1999).

Jones developed a detailed computer simulation program specifically for modelling the heat transfer in rooms with dynamic interior air temperatures and for various geometries, construction characteristics, and ventilation rates, which is used to develop simplified equations for nighttime ventilation control based on building mass temperature (Jones, 1996).

2-1-3 Air ventilation;

Any air exchange in buildings will constitute a heat loss or gain, depending on the building interior and exterior temperatures. The sensible heat flow rate due to air ventilation is represented by the following relation:

$$Q_v = 1200 \times v \times \Delta t(\quad W) \qquad \text{Eq. \#2-13}$$

Where:

1200 j/m C^o is the approximate volumetric specific heat capacity of dry air.

V = volume of air (m^2)

Δt = air temperature difference between room air and supply air (C°).

The use of environmental controls, such as air conditioning, has changed the design of residences. In multiunit housing, office buildings, and industrial buildings, mechanical systems are the practical means for utilizing natural ventilation.

Much research has been conducted to investigate potential energy saving by integrating air ventilation with other design elements. Markovic developed a mathematical model and software to analyse the efficiency of energy recovery by using 13 different energy control scenarios. He introduced recovered heat transfer and thermal comfort coefficients, cost rating for different controls, and the scenario to operate and size of the Recovery Heat Exchanger (RHE). He stated that the transfer of heat through an energy-to-energy recovery system might generate energy loss rather than energy saving if it is not fully understood (Markovic, 1993).

In his dissertation, titled “Predictive Equations For Nighttime Ventilation Control Based on Building Mass Temperature.” Jones found that reducing the temperature of the thermal mass of a building during the cooling season at night by circulating outdoor air throughout the building during unoccupied hours can reduce the daytime cooling load. He stated that “Selecting the ventilation runtime that is most cost effective while maintaining thermal comfort is rather complex (Jones, 1996).

Jones’ research concludes with two simplified equations for predicting the average surface and bulk mass temperatures. Computer simulation programs were written to model the building temperature response. Multiple regression was then applied to the simulation results to derive simplified prediction equations (Jones, 1996).

Research by Givoni targeted the relationship between thermal mass and night ventilation. In this research, buildings with different mass levels were monitored in the summer of 1993 in Pala, Southern California, under different ventilation and shading conditions. The effect of mass in lowering the daytime (maximum) indoor temperatures, in closed and in night ventilated buildings, was thus evaluated. The researcher found that night ventilation had only a very small effect on the indoor maximum air temperature of the low-mass building. However, it was very effective in lowering the indoor maximum air temperatures for the high mass building below that of the outdoor, especially during the `heat wave' periods. On an extremely hot day, with outdoor temperatures at a maximum of 38 degrees C (100 degrees F), the indoor maximum temperature of the high-mass building was only 24.5 degrees C (76 degrees F). This was within the comfort zone for the humidity level of California (Givoni,1998).

A study by Santamouris showed that utilizing night ventilation during the cooling seasons could save up to 30% of the seasonal cooling load (Santamouris, 1996). This study pointed out that selecting the most effective ventilation runtime while maintaining thermal comfort is rather complex and requires sophisticated computer programs to simulate buildings and apply multiple linear regression to derive simplified prediction equations for the specific designs.

Research by Kirkpatrick showed that convective heat transfer through apertures such as doorways could be an important process by which thermal energy is transferred from one zone to another in a building. They derived a model to predict the inter-zonal heat flow rate and heat transfer throughout the space (Kirkpatrick, 1988).

Another study by Messadi showed that detailed computer simulations reveal the effects and interactions that actually occur among the thermally massive room surfaces, solar radiation, and thermal insulation (Messadi, 1994). The study showed that only detailed computer simulation could handle the complexities required to accomplish a closer examination of this problem. However, this research did not establish a mathematical relationship between these design elements.

2-1-4 Latent heat storage;

The control of the indoor vapour content of an air-conditioned space, and hence of the relative humidity, has considerable importance in building design and thermal performance. Although relative humidity has a rather moderate effect on man's thermal comfort, humidity has a strong effect on mite, mildew, and bacteria growth in buildings. A study by Fletcher indicated that 45-85% of patients with asthma in the United Kingdom show skin test reactivity to mite, as compared with 5-30% in the general population (Fletcher, 1996). The feeding rate of mites is directly influenced by the ambient humidity (Arlian,1977), and the relative humidity should be sustained below 45% for several days to suppress mite growth (Colloff, 1991).

Vernacular architecture has successful examples of integrating thermal mass, moisture and pollutant absorbing materials, and air ventilation to control indoor air quality, Figure 2-4 presents a traditional house in Egypt with these strategies incorporated. The wind tower contains water jars to provide evaporative cooling on dry days and charcoal to absorb dust and pollutants on days with high particulate count levels.

Controlling latent heat load is strongly related to ventilation. Under the new ASHRAE Standard 62-1989, minimum outdoor air requirements for ventilation was significantly increased. In humid climates, these high ventilation rates contribute significantly to building cooling load, where latent heat can represent up to 38% of the building cooling load (Abaza, 2000).

Generally speaking, in air-conditioning practice, moderate relative humidity variations are permissible inside buildings. For instance, ASHRAE suggests that a typical indoor design conditions should maintain the indoor relative humidity at values ranging from 40% to 60%.

The moisture storage capabilities of internal surfaces may play an important role in latent loads calculations. As much as a third of the water vapour generated in a room can be absorbed by its surfaces (Planther, 2001). Although exhaustive analysis of these interacting effects may be technically important, until now such aspects have not been thoroughly investigated, and so far no single theory or explanation for moisture transfer in solids has been found (Plathner, 2001). Figure 2-5 and the following relations describe the basic principles of moisture transfer in porous materials; one-dimensional water vapour transmission through a porous material may be described as;

$$g = -\delta \frac{dc}{dx} \qquad \text{Eq. \#2-14}$$

Where;

g = water vapour transfer rate per unit area, kg/m² s

c =water vapour content inside the porous material, kg/m³

x = distance, m.

The vapour permeability, δ , is a characteristic quantity that depends mainly on the internal structure of the porous material, and only slightly on temperature. Materials with open pores generally have a larger δ than those having a rather closed pore structure. (Isetti, 1988).

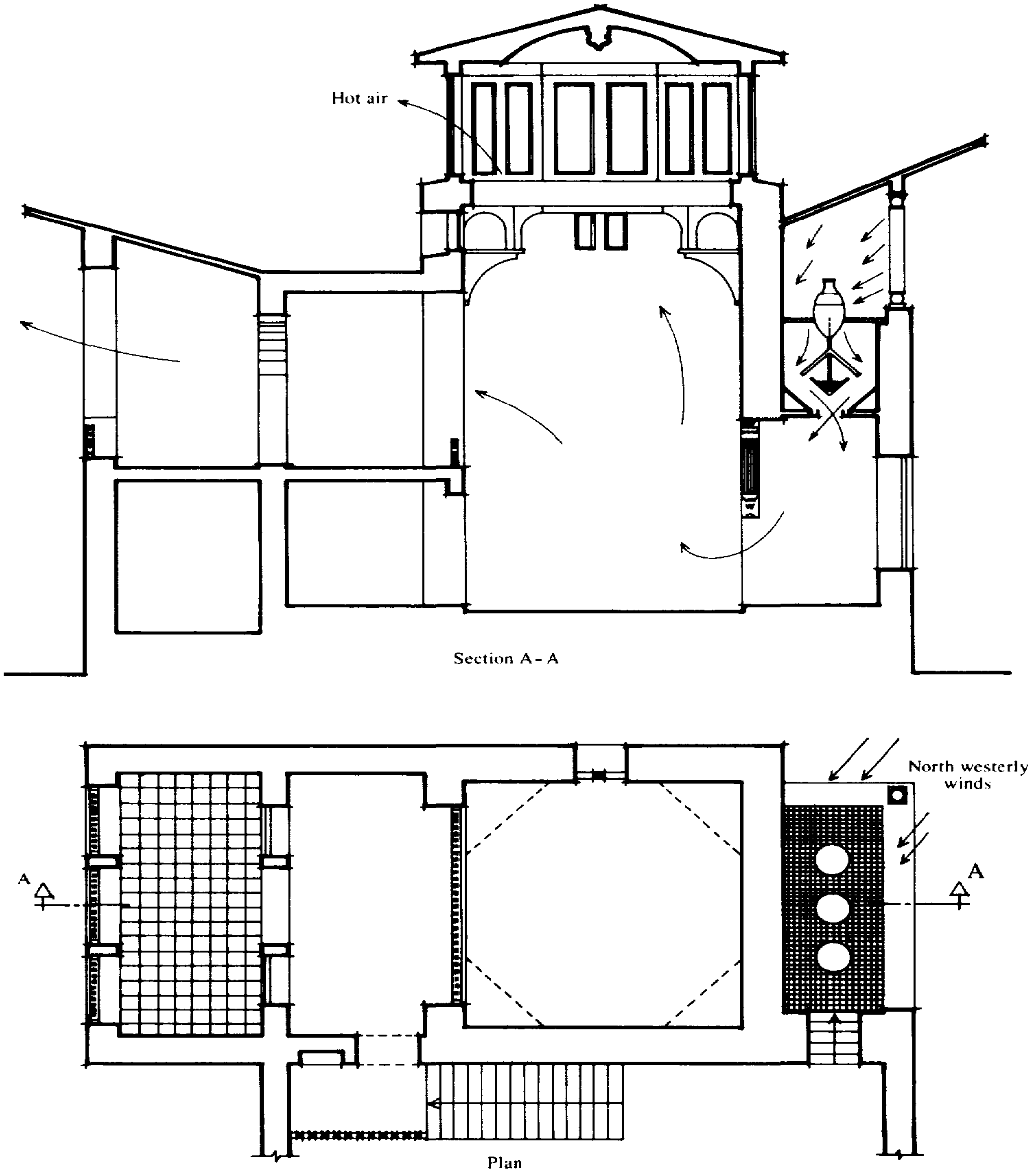


Figure 2- 4; Traditional building in Egypt.

(source: Fathy, 2001).

The vapour diffusivity of the material, D, depends directly on δ and inversely on the differential vapour capacity ξ which is defined from the absorption isotherms as ξ= ∂ψ/∂¡ . It holds that

$$D = \delta \times c_s / \rho \times \zeta$$ Eq. #2-15

Where

ρ = water density, kg/m^3

c_s = water vapour content of saturated air, kg/m^3

ψ = moisture content by volume (m^3/m^3)

¡ = room relative humidity (%).

The water vapour content in the indoor air can be determined by a water vapour balance equation where moisture storage capacity of the wall is considered:

$$V \frac{dc_i}{d\tau} = G + nV(c_o - c_i) + M$$ Eq. #2-16

where

V = volume of the room, m^3

c_i = water vapour content in the room, kg/m^3

c_o = water vapour content in the air supply, kg/m^3

G = moisture generation rate, Kg/s

n = air changes, s^{-1}

M = moisture rate absorbed in the room surface, kg/s

τ = time, s.

If the evaporative rate (er) is known and expressed in kg/h, the corresponding heat loss rate is:

$$Q_e = \frac{2{,}400{,}000}{3600}(J/s) = 666 \times er(W).$$ Eq. #2-17

Where 2 400 000 j/kg is the latent heat of evaporation of water.

The evaporation from or condensation on a unit surface area can be estimated as

$$w = 3600 \frac{sm}{R_s \times T}\left(p_{vf} - p_{vs}\right) \text{ in } \left(kg / m^2 h\right) \qquad \text{Eq. \#2-18}$$

Where

p_{vf} = vapour pressure in fluid,

p_{vs} = saturation vapour pressure at surface temperature,

T = absolute temperature of surface (K°)

Rs = gas constant (= 461 j/kg degC for water vapour),

sm = surface mass transfer coefficient = $\frac{h_c}{1200}$ Eq. #2-19

h_c = convection coefficient (w/m^2 degC).

Figure 2-5 summarizes the typical moisture transfer and generation in buildings.

2-1-5 Thermal Insulation;

From a high temperature zone heat will flow towards a lower temperature zone by conduction, convection, and radiation. Conduction is the spreading of molecular movement throughout an object in direct contact. The rate of this heat flow through a body depends on the cross-sectional area (A) taken perpendicular to the direction of flow, the thickness of the body (b), the temperature difference (Δt) between the two opposite

surfaces of the material, and the characteristic of the material known as conductivity or k-value, measured as the heat flow rate through a unit area and unit thickness of that material. The conduction heat flow rate (q) through a body can be determined by (Fourier's Law) which is given as

$$q = kA \frac{dt}{dx} \qquad \text{Eq. \#2-20}$$

Which in our notation can be written as

$$Q_c = kA \frac{\Delta t}{b} \qquad \text{Eq. \#2-21}$$

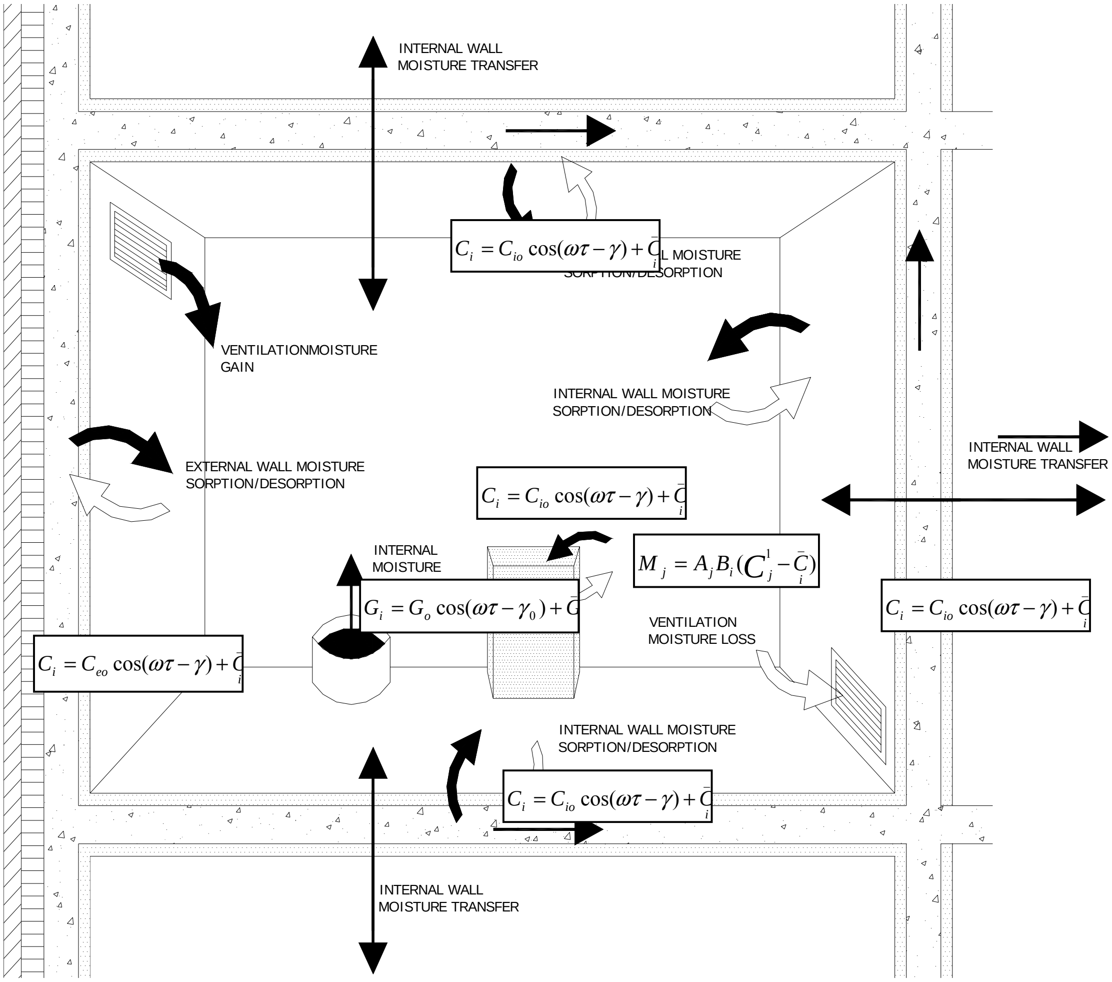


Figure 2- 5: Typical moisture transfer process in a building.

where;

Q_c =Conduction heat flow

k = conduction coefficient.

A = Area of contact between the body and the air.

Δt = Temperature difference between the body and the air.

Convection is the form of heat transfer from surface of a solid body to the air or visa versa. Convection also depends on the area of contact (A) between the body and the air, the temperature difference between the body and the air (Δt) and the convection coefficient (h_c) measured in W/m² degC.

The convection heat flow rate can be expressed by Newton formula

$$Q_v = h_c \times A \times \Delta t. \qquad \text{Eq. \#2-22}$$

Where;

Q_v =Convection heat flow

h_c = convection coefficient.

A = Area of contact between the body and the air.

Δt = Temperature difference between the body and the air.

The magnitude of h_c depends on the air velocity and whether the airflow is laminar or turbulent. Convection coefficient h_c is also depends on the air temperature, surface temperature, conductivity, specific heat of the air, shape of contact surface, and physical dimension of the system. The values of this convection coefficient between air and building surface is approximately 3.0 for vertical surface and 1.5 for air flow downward to floor (downward flow).

2-1-6 Air Conditioning System;

Much research has been conducted to investigate optimizing the selection of heating/cooling systems and their control strategies. A computer simulation program was prepared by Foster to simulate the efficiency of heat pumps under different operating conditions. In this model, if the designer inputs the supply air temperature, return air temperature, outside air temperature, and the size of the heat pump, the simulation program will predict the efficiency of the heat pump at different operating conditions (Foster, 1996). A mathematical model was developed by Markovic to analyse the efficiency of energy recovery. The results showed that energy savings can be obtained not only for scenarios with changing space heater sizing but also with varying valve control strategies (Markovic, 1993).

David described a multi-disciplinary team investigation for the performance of a variable-speed residential heat pump that was controlled by a modified home automation system. The main objective of this research was to modify the hardware and software of the home automation system so that it could effectively control a variable speed zoned HVAC system. This system saved over 49% in the heating mode and up to 47% in the annual cooling mode when compared to a fixed speed system (David, 1993).

2-1-7 HVAC Control strategies;

The control of HVAC systems has been the focus of much research over the past several years. The topics covered in this research include: proper control sequencing, the application of simplified response models and the application of neural networks to HVAC control, development of fuzzy logic and rough sets controllers, and non-linear HVAC control.

Much research has been conducted to investigate optimum air conditioning control strategies. Enebder developed a predictive controller based on the theory of optimal stochastic control to save energy and minimize overheating in buildings with significant solar gains. The predictive controller has been tested in passive solar rooms by computer simulation. A predictive controller prototype was developed and installed in an occupied office of a passive solar experimental building. The resulting energy consumption was 27% less for the predictive controller as compared to indoor temperature controller over the entire period. The savings varied between 0% for cloudy winter weeks to 60% for sunny spring weeks. The thermal comfort in the office with the predictive controller was also improved (Enebeder, 1997).

Yao developed an optimal predictive control methodology for real-time dynamic operation of the building heating systems. This control methodology integrates a weather predictor, set-point optimizer, feedforward control scheme, and an adaptive generalized predictive control algorithm to achieve a high level of thermal performance. The research suggests a simplified weather predictor through normalization, which quantifies the qualitative weather forecast for solar radiation. Using the predictions of solar radiation and ambient temperature, and the identified model of the heating process, the zone set point is optimized through online simulation. The adaptive generalized predictive controller associated with feed forward control scheme has been improved with a control algorithm capable of compensating for large thermal lags (Yao, C.,1996).

Mohammadi conducted research on using genetic algorithms to optimize controller parameters for HVAC systems. He introduced an adaptive learning algorithm based on a genetic algorithm for automatic tuning of the proportional, integral and adaptive controllers in HVAC systems to achieve optimal performance. The researcher argued that Genetic Algorithms, which are search procedures based on the mechanics of Darwin's natural selection, could obtain near optimal solutions for complex problem spaces such as HVAC control. The simulation results show that the genetic algorithm-based optimization procedures as implemented in this research are useful for automatic tuning of HVAC systems controllers, yielding minimum overshoot, and minimum settling times (Mohammadi, 1995). In a further step to integrate control systems, Peter proposed system for controlling lighting, ventilation, and indoor temperature of low-energy buildings. The simulation results with the proposed control system showed reduction in energy consumption by using the outdoor climate. The model proposed a control strategy for the movable shading devices and window ventilation. When compared with a simple on/off system, the integrated control system saved energy in moderate climates, while nearly maintaining almost the desired comfort level when operating in a passive mode (Peter, 1990).

Research by Mistry discussed the new family of easy to use speed controllers for HVAC systems, which offer continuously variable speed performance. These controllers were developed and launched by GPS in 1997 (Mistry, 1993).

In an article about the use of artificial intelligence and networking in integrated building management systems, Burne outlines how AI techniques can enhance the control of HVAC systems for occupant comfort and efficient running cost based on occupancy prediction, time of the day, and real time environmental conditions. This control strategy is based on a set of rules which govern the running strategy (Brune, 1997).

A research group lead by Zaheer conducted more than 32 studies concerned with optimizing the control of HVAC systems based on controlling the VAV system, variable chilled water flow, fan and pump speed, air distribution system and the piping system. They implemented a neural network, simulation, weather forecasting, and predicting the actual load logarithm to control indoor air temperature (Zaheer, 1994).

This team also suggested an optimal predictive control methodology for real-time dynamic operation of the building heating system. It integrates a weather predictor, set point optimizer, feedforward control scheme, and an adaptive generalized predictive control algorithm in order to achieve a high level of building thermal performance (Zaheer, 1994). However, this research does not consider other design variables such as natural ventilation, the trade-offs in the comfort parameters, or natural lighting. It also suggests fixed "optimum" solutions for running the HVAC systems, where decision makers have little choice of manoeuvring through the operation strategy while considering other design variables.

In an attempt to utilize the concept of system integration in controlling the heating and cooling systems in buildings. Mohammadi presented a new controller for the heating and cooling systems in buildings, which takes into account the thermal state of buildings as well as the outside air temperature. The TRNSYS simulation software was used to model a multi-zone building and several types of thermal control. The controller was tested for different configurations of thermal inertia, excess plant capacity, internal loads, and a set-point temperature for unoccupied periods (Mohammadi, 1995).

This approach allows the designer to control the HVAC system in light of its actual contribution to energy consumption. However, this model tests certain scenarios for running the HVAC system, but does not predict the contribution of each of the building elements to energy saving of the HVAC system. Thus, the designer can not consider other design variable when specifying the HVAC control system.

2-1-8 Thermal comfort;

The study of perception of heat is referred to as psychothermics. The skin perceives heat by a specialised type of nerve endings in the skin which is responding to temperature. These temperature sensors are most sensitive around 34°C, where small differences can be perceived. Towards the limits of the tolerable temperature (e.g., the 0°C and 46°C), the sensitivity rapidly decreased.

Fechner's Law states that response is proportional to the logarithm of the stimulus. This is applicable to psychothermics. The skin temperature (average 34°C) is taken as the reference point and the magnitude of the stimulus is measured as the deviation from this reference point in either direction.

Air temperature is the most important factor in determining thermal comfort, but not the only one. The various heat exchange processes at the body surface are influenced by a number of environmental factors. The sensation of comfort or discomfort depends on the joint effect of all of these. The most important factors of these are the relative humidity, air movement, and radiation.

Humidity of the atmosphere has little effect on thermal comfort sensation at or near the comfortable temperatures. It does however, play an important rule in the evaporative regulation zone. At comfortable temperatures there is no need for evaporative cooling. Both extremely low and extremely high humidifies have adverse effects. When relative humidity (RH) is less than 20%, the mucous membranes dry out and susceptibility to infection is increased. In warm situation, where the humidity of the air is above 60% RH sweat is produced; but it cannot evaporate: hence the familiar sticky feeling.

Air movement also produces thermal sensation, even without any change in air temperature, because it increases heat dissipation from the skin. Under hot conditions air velocity of 1m/s is considered pleasant, and velocity up to 1.50 m/s may be acceptable. Under cold conditions, in a heated room 0.25 m/s velocity should not be exceeded. However, in a heated room an air movement of less than 0.10 m/s will create the feeling of stuffiness. (Szokolay, 1980).

Radiant thermal exchange is also important. Radiation falling on the body surface activates the same sensory organs as the warmth of the air. Conversely, if the body is exposed to cold surfaces, a significant amount of heat is emitted in the form of radiation towards these surfaces. Such radiation emission causes a cold sensation. On average a 1C° drop in air temperature is compensated for by an incident radiation flux of 7W on the human body surface or 70W/m² (Szokolay, 1980).

Individuals can exert a considerable degree of control over most forms of heat exchanges between his body surface and the environment by choosing his/her clothes. The insulating cover of clothes is represented by the clothes *clo* factor, which corresponds to an average U-value of 6.5W/m² C° over the entire body surface. A normal lightweight business suit and cotton underwear is equivalent to 1 *clo*. Shorts, briefs, and short sleeve shirt is equivalent to 0.25 *clo*. Under still air conditions, when a person engages in a sedentary activity, the variation of 1 *clo* would be compensated for by 7 C° temperature changes (Stein,1991).

There is a range of subjective, non-quantifiable factor, which affect the thermal preferences of the individual by either changing the metabolic rate or influencing the heat dissipation mechanisms. For example, the acclimatization to the conditions of a location or of a season influences both the metabolic rate and the circulation of the individual, and thus individual performance. This acclimatization may last for up to six months. Age and sex, shape and body subcutaneous fat, condition of health, activity, food and drink are also important factor in thermal sensation.

Human response to the built environment may also be influenced by other factors such as behaviour adjustment by modifying the surroundings themselves (e.g. opining/closing windows and shades, or turning on fans or heating, etc.). Economics and energy cost also contribute to behavioural adjustment (Gail, 1998).

2-1-9 Statistical analysis;

The thermal response of building components and occupant behaviour is complex and interactive as discussed earlier. It is complicated to derive direct physical relations between the building components and the building thermal performance. Therefore, researchers use applied statistical analysis to derive relations between variables that govern the building thermal performance. The following basic statistical analyses are widely used in building thermal analysis, and will be used in this research;

2-1-9-1 Correlation;

The correlation coefficient is a common statistic analysis which shows the strength of the relationship between two continuous variables. The correlation coefficient is a number that ranges from –1 to +1. A positive correlation means that as values of one variable increase, the other variable will also tend to increase. A small or zero correlation coefficient indicates that the two variables are statistically unrelated. Finally, a negative correlation coefficient shows an inverse relationship between the variables.

The correlation analysis is usually associated with probability analysis, which shows the probability of obtaining a sample correlation coefficient as large or larger than the one obtained by chance only.

The significance of a correlation coefficient is a function of magnitude of the correlation and the sample size. One of the best ways to interprete a correlation coefficient (r) is to look at the square of r (r^2). R squared can be interpreted as the proportion of variance in one of the variables that can be explained by variation in the other variable.

Another consideration in the interpretation of correlation coefficient is to examine a scatter plot of the data. Because the odd extreme data points can cause the correlation coefficient to be much larger than expected, an important assumption concerning the correlation coefficient is that each pair of x, y data points is independent of any other pair. That is, each pair of points has to come from a separate subject.

2-1-9-2 Regression;

The regression line is the line that best represents the relationship between x, and y. That is, we can draw a line on the graph with most of the data points being only a short distance from the line. The vertical distance from each data point to this line is called a residual. A residual is the difference between a subject’s predicted score and his/her actual score.

In regression, the standard error (T) is testing the probability of obtaining by chance alone, a value as large or larger than the slope of the line. The standard error is a measure of the amount of error in the prediction of y for an individual x

The estimated relationship between the dependent variable and independent variables, for a given population sample, can be expressed by;

$y = b_o + b_1 x_1 + b_2 x_2 + ... + b_n x_n$ +e

Where,

y = the predicted dependent variable
$x_1 - x_n$ = the independent variable
bo = the intercept
$b_1 - b_n$ = the partial slope coefficients
e = residual

The partial slope coefficients (b) are taken from the analysis of variance output and represent the linear relationship between the dependent and the corresponding independent variable (Crawford, 1991). It is important to recognize that the relationship between the variables is assumed to be linear. When the relationship between the variables is not inherently linear, the shape of x-y curve from the scatter plot can be examined to suggest a transformation to achieve linearity. Advanced computer statistical analysis software can also predict and test data transformation.

The regression line seeks to minimize the sum of the squared errors of the prediction. The confidence interval on the slope of the regression line can be computed based on the standard error of the slope (S_b). The formula for the standard error of b is:

$$S_b = \frac{S_{est}}{\sqrt{\sum (X \_ X_M)^2}}$$

where S_{est} is the standard error of the estimate, and M is the mean of the predictor variable.

The formula of the standard error of the estimate is

$$S_{est} = S_y \sqrt{(1-r^2)} \sqrt{\frac{N}{N-2}}$$

Using the general formula for confidence interval which is b ± t where t is based on N-2 degree of freedom (df) and b is the slope of the line. The formula of t is

t= $df \times S_b$

Thus the confidence interval of a line is

$-t \leq$ population slope $\leq t$

When performing regression analysis, five conditions must be considered;

1. The vector sample observations on Y may be expressed as a linear combination of the sample observations on the explanatory X variables plus a disturbance vector. This also means that all significant variables are included and no extraneous variables are present.
2. The expected value of disturbance is zero; if this assumption is violated, the slope coefficient estimates remain un-biased but the intercept term may not be.
3. Constant variance and pairwise uncorrelated disturbance; when applying OLS, the variance and the disturbance (e) should be constant and pairwise uncorrelated. It is common for the disturbance to be pairwise correlated, particularly for time series data where residuals are often correlated with residuals lagged one or two time steps. High cross-correlation between lagged and unlagged residuals is termed autocorrelation. When autocorrelation is present the slope coefficient estimates remain unbiased but their standard errors are likely to be too high or low.
4. The X variables do not form a linear dependent set; which means that the variation of one or more of the independent variables should not be explained by the remaining independent variables (multicollinearity).
5. X is a non- stochastic matrix; The assumption that x is a non-stochastic matrix implies that for different experimental data and analysis, the set of independent

variables included in the model remains unchange; This suggests the modelled process is consistent and repeatable under controlled conditions.

6. The disturbance is normally distributed; that is, if all of the residuals from the analysis were plotted, the distribution should be centred on zero and has a normal bell-shaped distribution.

2-2 Whole Building Evaluation;

Prior researchers concluded that the effects of the major building components on energy consumption are integrated and require comprehensive computation and study as we will discuss later in this chapter. Much computer simulation software has been developed to simulate the overall building performance. Some of this software does this while concentrating on one particular aspect of the building, such as solar radiation, thermal insulation, natural lighting, mechanical systems, or natural ventilation. An example of these kinds of analysis tools is EnergyPro, a comprehensive energy analysis program that performs several different energy calculations. EnergyPro is composed of an interface, which includes a building tree, a set of libraries, and a database of state-certified equipment directories. This software can produce room-by-room load calculation reports and HVAC psychometric diagrams (EnergPro, 2001). Samir studied the roof color building, orientation, wind speed, and the utilization of an attic radiation barrier system. The results showed that these design considerations have the potential of reducing energy consumption substantially, especially during the cooling periods (Samir, 1992).

Another study was conducted using simulation models to quantitatively define the amount of available solar radiation, heat gain, and shading. It is hoped that the results will be used to reduce the heat islands over cities, which, in turn, will eventually reduce the cooling load for each individual building (Obeidat, 1995).

EnergyPlus is another software, which introduces new approach to energy analysis. EnergyPlus is an energy analysis and thermal load simulation program.
Based on a user’s description of a building from the perspective of the building’s physical

make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control set points, conditions throughout an secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building.

The BEANS Software is a comprehensive building simulation and analysis software developed by ARUP company. The energy simulation engines in BEANS combine thermal, lighting, solar radiation, air ventilation, and HVAC system simulation (BEANS, 1997).

Solar-5 is an early generation of computer simulation, which provides data visualization of building performance (Solar-5, 2002)

EnerWin building energy simulation software is a simple simulation model which is written in FORTRAN, and provides a base for integrating other simulation and optimization techniques to explore building performance. (Enerwin, 1995).

TRNSYS software is an advanced simulation tool, which provides detailed simulation for building performance and tests the performance of the different parts of the HVAC system and passive design techniques (TRNSYS, 1995).

These computer programs usually provide the designer with a relatively accurate and comprehensive performance of the selected design from an energy point of view. These tools simulate the proposed design to predict its energy performance. However, these computer programs shortcoming is that they do not provide designers with a clear picture of the potential energy saving by exploring other design alternatives.

2-2-1 Systems Integration;

In their effort to build a holistic evaluation tool of energy conservation in buildings, many researchers geared their efforts towards developing multi-aspects simulation and evaluation tools. Several comprehensive computer programs have been developed to create these evaluation and simulation tools. These are generally comprehensive and take into consideration a wide range of design variables, such as direct and indirect solar radiation, natural ventilation, building location and orientation, daylight, mechanical systems, thermal comfort parameters, activity patterns, as well as building regulations and cost.

One such tool is the knowledge-based computer-aided architectural design system, KB-CAAD. It is used for the schematic design and evaluation of passive solar buildings, introduced by Shaviv. This system is based on the integration of knowledge-based and procedural simulation methods with the CAAD system for building representation. The knowledge base contains the heuristic rules for the design of passive solar buildings. Whenever possible, the knowledge base guides the designer through the decision-making process. However, if the rules of thumb are not acceptable for a particular design problem, the KB-CAAD system guides the architect by using a procedural simulation model. (Shaviv, 1990).

Another example of these tools is Building Design Advisor (BDA) developed by the Lawrence Berkley Lab. BDA is a Windows computer program that addresses the needs of building decision-makers from the initial schematic phases of building design through the detailed specification of building components and systems. The BDA is built around an object-oriented representation of the building and its context, which is mapped onto the corresponding representations of multiple tools and databases. It then acts as a data manager and process controller, automatically preparing input to simulation tools and integrating their output in ways that support multi-criterion decision making (BDA, 2000). However, this program provides the performance of each design solution in general, and does not investigate the potential contribution of each design element nor does it address the relationships among these elements in terms of energy saving.

ENERGY-10 software is another example of a tool developed to evaluate and advise designers on energy conservation. This software provides a quick way to automatically evaluate energy-efficient strategies revealing the individual effect of each building component on energy consumption. It also makes global modifications in building descriptions. These modifications are made based on the designer’s selection of any or all the building components and the characteristics he/she may select.

ENERGY-10 first simulates the unmodified building, applies the first strategy selected, does a simulation, saves some results, and finally, returns the building to its unmodified form. It proceeds automatically through all the selected strategies in the same way. At the conclusion, it displays the results, which are ranked according to annual energy saving. The user can then select other ranking criteria.

ENERGY-10 also generates an alternative design, which is derived from the reference case (the base design which is supplied by the user) and applies energy-efficient strategies. Those that might be added are: insulation, energy-efficient lights, daylight, passive solar heating, and extra mass for heat storage. The user gets to select the strategies. This second building, called the low-energy case, is evaluated and the results are displayed alongside the reference case results. This shows the potential for savings from the selected strategies. Again, it also automates the process of sequentially applying several energy-efficient strategies of potential interest, evaluating their consequences, and ranking the results (Douglas 1999).

This software provides the potential savings of suggested pre-defined strategies. These strategies are based on suggested values for the main building design elements. However, this software pre-defines the building alternatives which best serve energy conservation making this tool fall short of the designer's goal of selecting design alternatives while taking into consideration other design interest. Furthermore, this tool does not provide the designers with the range of potential energy saving which may be achieved when selecting building variables other than the "optimum" value. Finally, ENERGY-10 does not demonstrate the relationship between the main design elements, such as thermal insulation, thermal mass, and natural ventilation.

To overcome this obstacle, researchers investigated how to derive relationship between all the building variables and the associated building performance. Modera developed a generalized methodology for determining the total heat gain through building envelopes (Modera, 1995). The methodology was based on the concept of overall thermal transfer value equations for building envelopes, which is developed through parametric simulation using DOE-2 computer code. It is hoped that these methods will allow designers to make more accurate estimates of the total heat gain for the purpose of evaluating energy efficient building envelope components, air-conditioning systems, and plant options.

Many studies developed an "intelligent" CAD system to assist the designer throughout the design activity. To achieve this goal, these studies incorporated the design advisories of several experts with different knowledge databases. These experts would have the ability to interact in real time in order to monitor the evolving design in several domains. These studies illustrated an effort to support design flexibility and allow designers to shift their focus from one consideration to another without controlling their activities. As a result, most of the systems that are produced by these studies have the ability to resolve conflicts among the domain experts.

An example of such a system is ICAD, an intelligent computer-aided design system advisor. It has six knowledge systems working as domain experts: a blackboard-coordination expert, two knowledge bases and several sources of reference data. The expert design advisor is responsible for the evaluation of the evolving design solution and the resolution of conflicts that may arise when solutions in one domain interfere with a solution in another domain (ICAD, 1992).

The domain experts that the system includes are access, climate, cost, lighting, sound and structure. The system contains a geometry interface capable of extracting architecturally meaningful geometric objects. This system uses the approximate evaluation for its calculations and recommendations in relation to the overall energy efficiency (ICAD, 1992).

Malkawi developed an intelligent computer-aided thermal design model. This model first simulates the energy performance of a building. At the same time, it provides advice and a critique of the existing design, taking into account possible element interactions and conflicts. Criticism and advice are given based on problem detection and their locations using artificial intelligence uncertain reasoning (Malkawi, 1994). A weakness in this tool is that it bases its advice on general energy rules suggested by previous research, which do not always produce an accurate assessment of energy consumption in buildings.

2-2-2 Computer-Designer Interaction;

Although both computer simulation programs and “intelligent” CAD system contribute significantly to energy conservation, they cannot cover all design aspects. These computer simulation and optimization models usually target the design process from specific physical design aspects. The designer has a major role in evaluating the design from a holistic point of view and producing innovative techniques to conserve energy while considering other design aspects such as aesthetic, human needs, function, practical operating strategies, practical construction techniques, as well as the particular specifications of the owner.

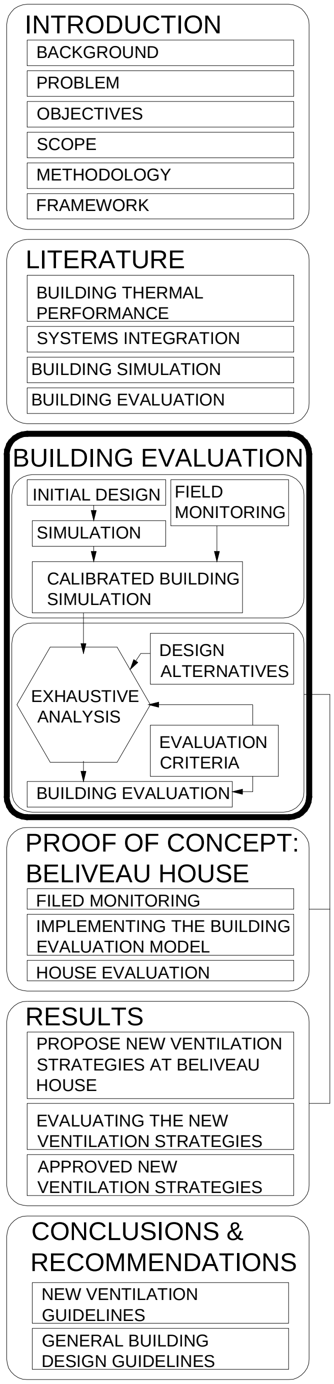
These expert systems usually provide suggestions or a single optimum solution based on a limited database as we discussed earlier which the designer may reject or accept. At the same time, the expert systems do not paint a clear picture of the contribution of each design element to energy conservation for the designer.

The goal of this research is to close this gap. The proposed model from this research will provide a range of potential energy saving of alternatives for each design elements. This model will establish the relationship between these design elements and energy saving in a form of mathematical equations and data visualization.

In order to test the proposed evaluation model and the air ventialtion control system, a field study and a computer simulation were conducted on the Beliveau House in Blacksburg, Virginia. The house designer, Professor Yvan Beliveau, implemented new ideas of integrating solar radiation, thermal mass, thermal insulation, and air ventilation to conserve energy. The goal of this study is to investigate the holistic contribution of these ideas to energy saving, and to extract the relationship between these design variables. The establishment of these relationships will also be used to predict the best air ventilation control strategies.

Chapter Three

III: Building Energy Conservation Evaluation Model.



III. Building energy conservation evaluation model;

This chapter discusses the components and procedures of developing a holistic evaluation model. The evaluation model simulates energy consumption in a building, analyzes a range of alternative solutions, and then derives relations between the suggested building component alternatives and the resulting energy consumption. The evaluation model consists of CAD interface, an alternative solutions generator, a building simulation generator, and a data analysis interface. Figure 3-1 presents the building evaluation structure overview.

3-1 CAD Interface;

To obtain the design attributes required for simulation, the building is drawn in a CAD tool. Designers usually draw the preliminary design into Auto-CAD© using 2D modelling. In order to transfer the building configuration in 2D CAD drawings into attributes that can be input to feed the simulation software, the building configuration in the Auto-CAD drawings is transferred into separates “regions”. Each region represents a

building component, as described by its size, location, and orientation. These regions are exported as DXF files. EnergyPlus© work directly with DXF files.

3-2 Solution generator;

In this phase, the designer proposes a base design solution and provide the initial data required for the building energy simulation, which includes a complete base design and yearly weather data for the intended building location. The physical characteristic of the

building, the mechanical, electrical, as well as the acceptable comfort level parameters should be specified in order to simulate the energy performance of the building.

3-2-1 Energy Simulation Software selection;

In order to simulate the building energy performance the EnergyPlus simulation tool was chosen. EnergyPlus was developed from both the BLAST and DOE–2 programs. BLAST

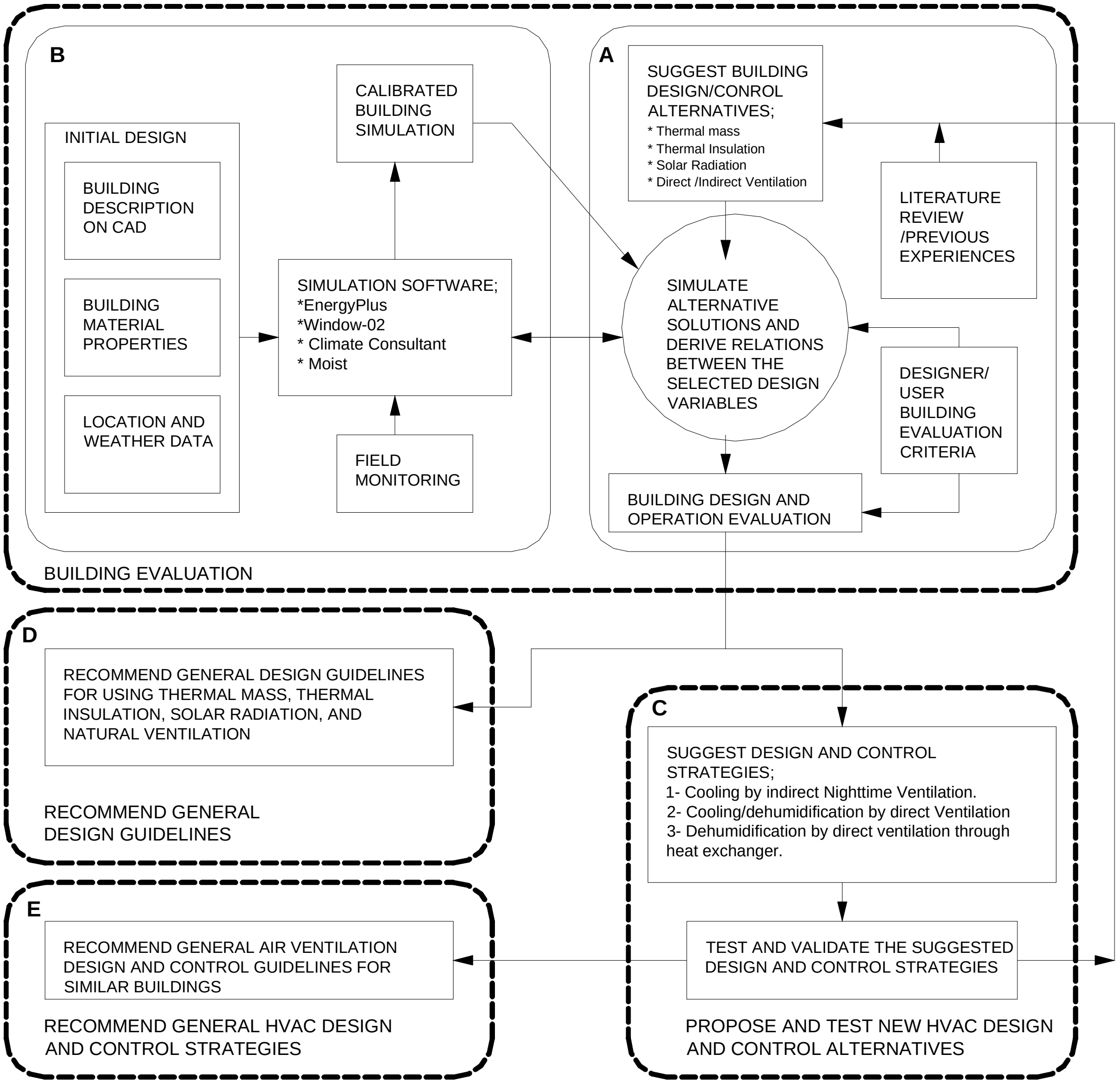


Figure 3- 1: Building evaluation structure overview

(Building Loads Analysis and System Thermodynamics) and DOE–2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools. Their intended audience are design engineers or architects that wish to size appropriate HVAC equipment. Based on user description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control setpoints (EnergyPlus, 2001).

The list below provides some EnergyPlus features ;

- EnergyPlus integrate building and HVAC systems and perform simultaneous simulation where the building response and the primary and secondary HVAC systems are tightly coupled. It can also perform iteration when necessary.
- EnergyPlus can perform simulations on sub-hourly or user-definable time steps. This variable time steps improves the interactions between the thermal zones and the HVAC systems.
- EnergyPlus accepts ASCII text based weather, input, and output files that include hourly or sub-hourly environmental conditions. This feature is significant to build the evaluation model since multi-simulation is required.
- EnergyPlus performs a heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at interior and exterior surfaces during each time step.
- EnergyPlus performs transient heat conduction through building elements such as walls, roofs, floors, etc. using conduction transfer functions.
- EnergyPlus has an improved ground heat transfer modeller that links to three-dimensional finite difference ground models and simplified analytical techniques
- EnergyPlus performs combined heat and mass transfer modeler that accounts for moisture adsorption/desorption either as a layer-by-layer integration into the conduction transfer functions or as an effective moisture penetration depth model (EMPD). This feature is significant in this research since both sensible and latent thermal storage are considered to balance the heating and cooling loads.

- EnergyPlus perform advanced fenestration calculations including controllable window blinds, electrochromic glazing, layer-by-layer heat balances that allow proper assignment of solar energy absorbed by window panes, and has a performance library for commercially available windows and shading.
- EnergyPlus builds loop based configurable HVAC systems that allow users to model typical systems and slightly modified systems without recompiling the program source code.

EnergyPlus facilitates links to other simulation environments such as WINDOW5, COMIS (airflow model), TRNSYS, and SPARK to allow more detailed analysis of building components. No program is able to handle every simulation situation, however, EnergyPlus handles many building and HVAC design options either directly or indirectly through links to other programs in order to calculate thermal loads and/or energy consumption for a design day or an extended period of time.

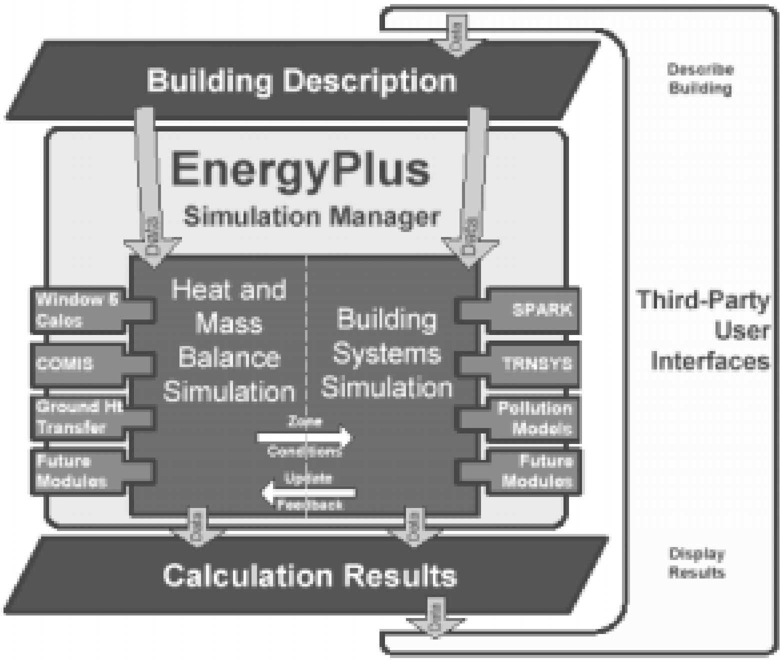


Figure 3- 2: Overview of EnergyPlus which explains the integration of EnergyPlus with other computer simulation software (source; EnergyPlus,2001).

- EnergyPlus performs integration of Loads, Systems, and Plants; one of the strong points of EnergyPlus is the integration of all aspects of the simulation loads, systems, and plants. Based on a research version of the BLAST program called IBLAST, system and plant output is allowed to directly impact the building thermal response rather than calculating all loads first, then simulating systems and plants (EnergyPlus,2001).

  EnergyPlus can investigate the effect of under-sizing fans and other equipments and what impact that might have on the thermal comfort of occupants within the building. Figure 3-2 shows a basic overview of the integration of these important elements of a building energy simulation.

  EnergyPlus is an "Open" Source Code software. The source code of the program is available and open for public adoption (EnergyPlus, 2001).

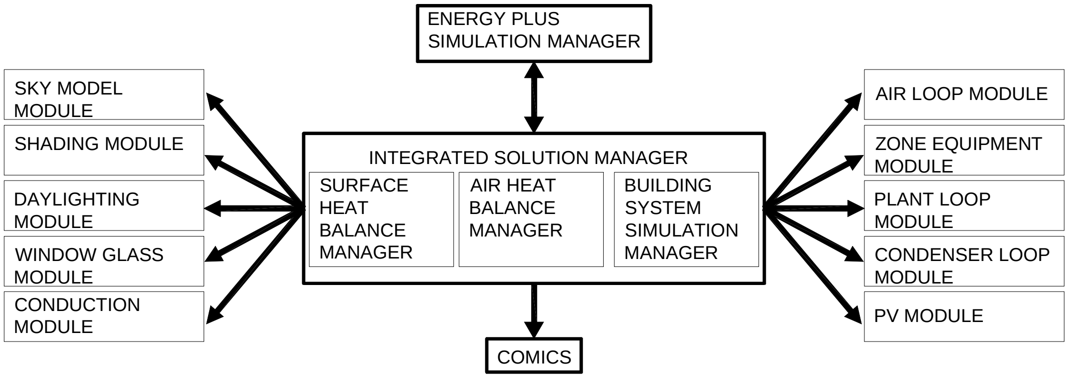


Figure 3- 3: EnergyPlus elements.

3-2-2 Base design generation;

In order to accurately predict the energy performance of buildings, the following design variables are considered in the building simulation:

3-2-2-1 Site data;

The designer should specify the site characteristics including elevation, orientation, ground cover, building exposure rate, latitude, longitude, time zone, elevation, holidays, and daylight saving period.

3-2-2-2 Weather Data;

The weather data used by EnergyPlus contains much of the same data in the Typical Meteorological Year (TMY) files, which is a data set of hourly values of solar radiation and meteorological elements for a 1-year period. It consists of months selected from individual years and concatenated to form a complete year. A TMY file provides a standard for hourly data for solar radiation and other meteorological elements that permit performance comparisons of system types and configurations for one or more locations. The weather data file contains the following weather variables;

Dry Bulb Temperature
Dew Point Temperature
Relative Humidity
Atmospheric Pressure
Wind Speed
Wind Direction
Total Sky Cover
Opaque Sky Cover
Visibility
Precipitable Water
Aerosol Optical Depth
Broadband turbidity
Snow Depth
Days Since Last Snow

Radiation Values (Direct/Diffuse)
Illuminance Values

3-2-2-3 Comfort Parameters;

Comfort parameters can have a large impact on energy conservation. In simulation, the designer may determine the range of the inside air temperature, relative humidity, mean radiant temperature, air ventilation rate, and air speed.

EnergyPlus software uses Franger’s comfort equation to express thermal comfort in a space in terms of PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfaction). Franger’s comfort equation is empirical and is based upon statistical data gathered in working environments. Fanger assumed that thermal sensation is a function of the thermal load of the body. The thermal load is defined as the difference between the internal heat production, and the heat loss to the actual environment for a person with (theoretical) mean skin temperature and sweat secretion at a given activity level (Fanger, 1972). It also takes into account the effects of humidity, room temperature, inside mean radiant temperature, air speed, and the heat given off by occupants, as well as their level of activity.

3-2-2-4 Building Fabric;

The designer specifies all construction materials, construction composition of all internal and external elements, condensation conditions, heat transfer of the internal and external surfaces, building envelope thermal and vapour resistivity, material thickness, material density, absorbtivity of inward facing, surface heat flow angle, surface reflectivity, and long wave, and short wave surface emissivity.

Unlike conventional thermal analysis methods such as environmental temperature and the admittance methods used in the simulation programs, EnergyPlus software uses more rigorous calculations for the dry resultant temperature and the dry bulb temperature in the occupied zone.

EnergyPlus models the heat flow through the slab by introducing the concept of “thermal capacitance”. This thermal capacitance adds a time delay to the temperature and heat flows that are predicted in the slab.

The calculation of radiant form factors is essential to the assessment of radiant heat flow: EnergyPlus calculated these factors for each surface in the space. EnergyPlus also dynamically calculates the heat conduction through the enclosure surfaces with time steps adjusted by the program.

3-2-2-5 Glass properties;

The designer defines the glass proprieties which include reflectance, light transmittance, light reflectance for the inward and outward facing surface, thermal short wave transmissivity, thermal long wave transmittance, thermal short wave reflectance for both inward and outward surface, glazing area, cavity size between glass and the cavity ventilation rate if it is ventilated. If the cavity between the two glass layers is not ventilated, the designer should specify the gas property which fills the cavity between glass layers. If window blinds are used, the designer may specify the operation pattern of the blinds.

For global analysis, EnergyPlus carries out an analysis of the radiant field at each analysis point in the occupied zone. A person is assumed to exist at each analysis point and a heat balance can be established at the surface of the person. Angle factors are used to evaluate the surface/subject radiant exchange.

In calculating solar radiant gain in buildings, the EnergyPlus program takes into account the spatial arrangement of the surfaces and the way each surface affects other surfaces. This makes it possible for the sunlight falling on each surface to be treated separately. This feature is significant in predicting thermal comfort when utilizing nighttime ventilation.

EnergyPlus based the comfort level simulation on predicting the mean radiant temperature (MRT) as well as the air temperature, relative humidity, and air movement. Furthermore, using a theory developed by Fanger, EnergyPlus tracks the path of sunlight in the space and modifies the MRT (at each hour) to include the effect of direct solar radiation if the analysis point is not shaded.

3-2-2-6 Mechanical system variables;

In EnergyPlus, there are several portions to the HVAC simulation. All of these parts must be correctly specified in order to arrive at a valid simulation model. An EnergyPlus HVAC simulation consists of various components that are connected physically in the actual system by ducts, piping, etc. Every component in an HVAC system must have an inlet and outlet “node”. In the actual system, a node might be a point in the system at which fluid properties can be measured. In an EnergyPlus simulation, the nodes are points at which fluid properties are evaluated and passed on to subsequent equipment.

Components are linked together to form various loops within the simulation. Thus, the inlet node from one component also serves as the outlet node to the next component. Loops are constructed by defining these loops and also defining the components on the loops. EnergyPlus specifies the mechanical system in six loop section types which are as follows;

Air Loop: The air loop is defined by the section of the zone/air loop that starts after the zone return streams are combined and continues on until just before any air stream(s) are branched off to individual zones. It includes outside air controllers, heat exchangers, desiccant dehumidifiers, fans, etc.

Zone Equipment: The zone equipment section of the input file includes everything from where the ducts are split to serve various zones up through where the return ducts from various zones are mixed into a single return duct. Zone equipment include dampers and reheat coils as well as zone specific conditioning systems such as thermostatic baseboard or a window air conditioner. Most control issues are typically dealt with in the zone equipment section of the simulation.

Plant Loop Demand Side: One side of the plant is where energy is “demanded” by various components that make up the air loop or zone equipment. Typically, this is the water side of equipment such as coils, baseboard, radiant heating and cooling, etc. The demand side of this loop can also include mixers, flow splitters, and a bypass.

Plant Loop Supply Side: The other side of the plant loop is where energy is “supplied” by various components. The components typically found on the supply side include pumps, boilers, chillers, purchased heating and cooling, ice storage, etc. As with the demand side, this loop can also include mixers, flow splitters, and a bypass.

Condenser Loop Demand Side: The condenser loop demand side is analogous to the plant loop demand side. In the case of the condenser loop, energy is typically "demanded" by a chiller condenser.

Condenser Loop Supply Side: This side of the condenser loop consists of the cooling tower, well water, etc. type components. It supplies (rejects) energy that would then be used at the chiller condensers on the other side of the loop.

The designer shall determine the performance of the different HVAC system components such as the maximum sensible efficiency of the different devices, maximum latent efficiency of the device, compressor motor rating (kw), total air follow pressure drop, compressor motor rating (kw), evaporator contact factor, bypass air percentage, number of heat pump stages, compressor load, maximum permissible relative humidity, fan efficiency, maximum efficiency of sensible and latent heat recovery device, coefficient of performance of the compressor, mechanical ventilation flow rate (ac/h), boiler efficiency, and overall heating plant efficiency. Figure 3-3 shows EnergyPlus different simulation component

3-3 Design alternative Solution Generator;

After establishing the base design, the designer selects building components, and then tests the overall affect on energy consumption. The designer establishes a matrix of ranges of the building component alternatives such as a range of wall insulation thickness, window glass properties, roof and exterior walls solar radiation absorption, natural ventilation rates, or comfort level set points. However, the scope of this research is limited to investigating the contribution of the thermal mass, thermal insulation, solar radiation, and natural ventilation flow rate. The designer specifies the ranges of the above design variables.

While establishing the ranges of building component values, the designer may take into consideration other design aspects such as aesthetics, cost, desired construction means and methods, and function. The solution generator accesses both the base design and the matrix of alternative solutions, assign one design alternative for each solution and save it in an appropriate format (the format required for EnergyPlus simulation software).

The end product of this solution generator is a matrix of complete design solutions input files, which are passed to the EnergyPlus simulation software. Figure 3-4 illustrates the solution generator interface.

3-4 Simulation generator;

The simulation generator transfers EnergyPlus with the input files generated by the solution generator as discussed early. EnergyPlus run the required simulation engines and produces the required output. Figure 3-5 shows the framework of the simulation generator. EnergyPlus has the following energy simulation modules;

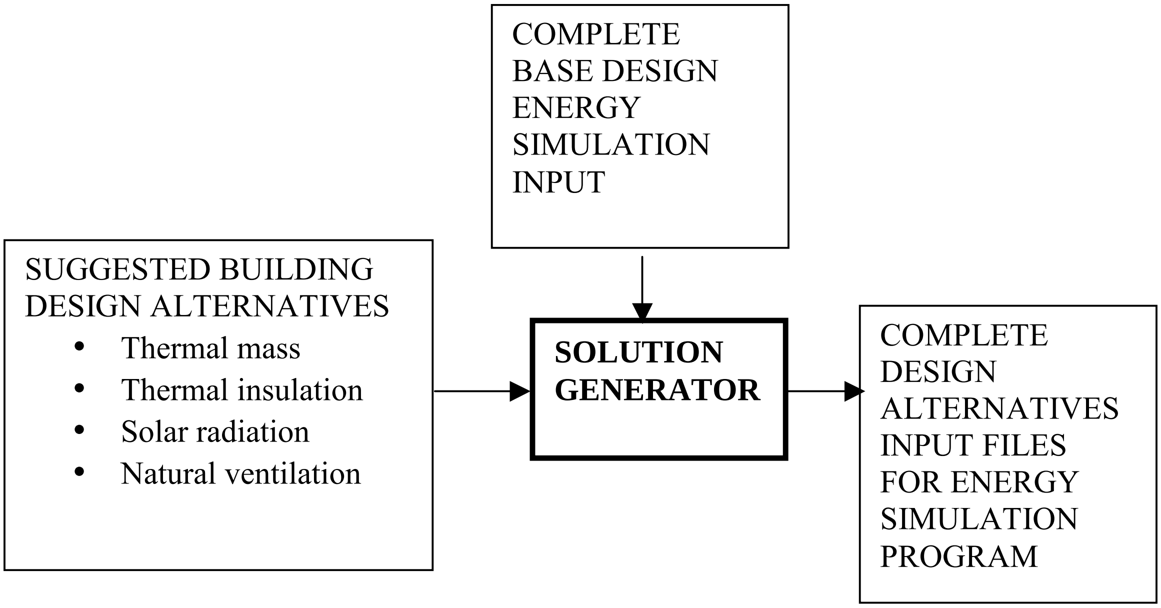


Figure 3- 4: The solution generator schematic diagram.

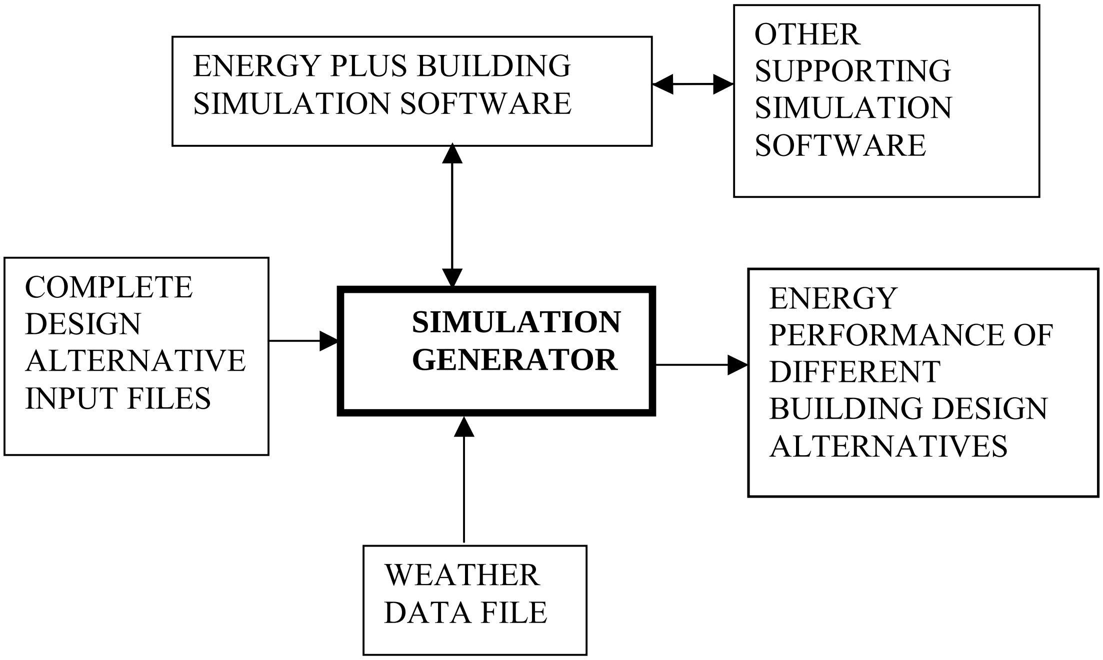


Figure 3- 5 : Building Simulation Generator.

3-4-1 Air heat balance module;

This module simulates the thermal behaviour of the building, which includes the following heat flow mechanisms;

3-4-1-1 Convection from Surfaces;

This contribution is expressed using the convective heat transfer coefficient as follows:

$$q_{conv} = \sum_{i=1}^{nsurfaces} h_{c,i} A_i (T_a - T_{s,i}) \qquad \text{Eq. \#3-1}$$

where;

q_{conv} = Convention heat transfer.

$h_{c,i}$ = Convention coefficient.

A_i = Surface area

$(T_a - T_{s,i})$ = Temperature difference between inside air and the surface

Convection from Internal Sources is the companion part of the radiant contribution from internal gains

3-4-1-2 Infiltration/Ventilation;

In EnergyPlus, any air that enters by way of infiltration is assumed to be immediately mixed with the zone air. The determination of the amount of infiltration air is quite complicated and subject to significant uncertainty. In the most common procedure, the infiltration quantity is converted from a number of air changes per hour (ACH) and included in the zone air heat balance using the outside temperature at the current hour. Air exchange and interchange between zones is treated as a convective gain.

3-4-1-3 Zone Air Temperature;

The zone air heat balance is the primary mechanism for linking the loads calculation to the system simulation. As such, the zone air temperature becomes the main interface variable.

The calculation results of EnergyPlus include the following variables;

- Dry bulb temperature, wet bulb temperature and relative humidity inside the building.
- Total incident solar radiation intensity on the south, southeast, southwest, north, northeast, east, northwest, and on the horizontal surfaces.
- Radiation and convection heat gain from occupants, mechanical components, and radiation and convection heat gain from lighting.
- Ventilation and infiltration heat gain/loss.
- Total sensible and latent heating gain or loss.
- Predicted mean vote comfort (PMV), and predicted percent dissatisfaction (P.P.D. %) .

3-4-2 Surface heat balance module;

This tool simulates the heat transfer through internal and external walls which includes;

- **Outside surface heat balance;** The heat balance on the outside face consists of the absorbed direct and diffuse solar (short wavelength) radiation heat flux, long wavelength (thermal) radiation flux exchange with the air and surroundings, convective flux exchange with outside air, and conduction heat flux in the wall.

- **Inside Heat balance;** This heat balance is generally modelled with four coupled heat transfer components: conduction through the building element, convection to the air, short wave radiation absorption and reflectance and long wave radiant interchange.
- **Sky radiance modelling;** In EnergyPlus the calculation of diffuse solar radiation from the sky incident on an exterior surface takes into account the anisotropic radiance distribution of the sky.
- **Shading Module;** EnergyPlus calculates the sky long-wave radiation incident on exterior surfaces assuming that the sky longwave radiance distribution is isotropic. If obstructions such as overhangs are present the sky long-wave incident radiation on a surface is multiplied by the isotropic shading factor.

3-4-3 Window Calculations Module(s);

In EnergyPlus a window is considered to be composed of the following four components:

- **Glazing**, which consists of one or more plane/parallel glass layers. If there are two or more glass layers, the layers are separated by gaps filled with air or another gas. The glazing optical and thermal calculations are based on algorithms from the WINDOW 4 and WINDOW 5 programs (Window 5.0, 2000).

  In EnergyPlus the optical properties of individual glass layers are given by the following quantities at normal incidence as a function of wavelength Transmittance, front reflectance, and back reflectance.
- **Frame**, which surrounds the glazing on four sides.
- **Divider**, which consists of horizontal and/or vertical elements that divide the glazing into individual lites.
- **Shading device**, which is considered as a separate layer, such as drapery, roller shade or blinds, on the inside, outside of the glazing, or between the two glass panes. The purpose of the shading device is to reduce solar gain or control daylight glare.

Shading devices affect the system transmittance and glass layer absorptance for short-wave radiation and for long-wave (thermal) radiation. The effect depends on the shade position (exterior or interior), the shade transmittance, and the amount of inter-reflection between the shade and the glazing.

Window shades are either fixed or moveable. If moveable, they can be deployed according to a schedule or according to a trigger variable, such as solar radiation incident on the window.

- **Exterior Non-Insulating Shade**

It is assumed that an exterior non-insulating shade has no effect on the exterior long-wave radiation from sky and ground reaching the outside glass surface.

- **Exterior Insulating Shade,**

Exterior insulating shades are assumed to be opaque to long-wave radiation. In the glazing heat balance calculation, a shade of this type is combined with the outside glass layer into an effective single layer with a thermal resistance that is the sum of the shade and glass resistance. The outside of this layer is the outside of the shade; it absorbs long-wave radiation from the sky and ground and emits long-wave radiation depending on its temperature and thermal emissivity.

- **Interior Non-Insulating Shade;**

EnergyPlus assumed that an interior non-insulating shade has no effect on the interior long-wave radiation from other room surfaces reaching the inside glass surface. It is further assumed that an interior non-insulating shade absorbs no long-wave radiation from other room surfaces. It is also assumed that all of the heat from the shade both radiative and convective convects immediately into the zone air, so neither the window nor other room surfaces receives long-wave radiation produced by the shade. However, the presence of an interior non-insulating shade is accounted for calculating how much long-wave radiation from zone equipment and lights is absorbed by the shade and by the inside glass surface.

3-4-4 Building system simulation;

The Building Systems Simulation Manager controls the simulation of HVAC and electrical systems, equipment and components, and updates the zone-air conditions.

EnergyPlus does not use the sequential simulation method found in DOE–2 and BLAST (first building loads, then air distribution system, and then central plant) since this imposes rigid boundaries on program structures and limits input flexibility (EnergyPlus,2001). Instead, the building systems simulation manager integrates simulation of loads, systems, and plant.

EnergyPlus uses loops throughout the building systems simulation manager primarily HVAC air and water loops. Loops mimic the network of pipes and ducts found in real buildings. The air loop simulates air transport, conditioning and mixing, and includes supply and returns fans, central heating and cooling coils, heat recovery, and controls for supply air temperature and outside air economizer. The air loop connects to the zone through the zone equipment diffusers, reheat/recool coils, supply air control (mixing dampers, fan-powered VAV box, induction unit, VAV dampers), local convection units (window air-conditioner, fan coil, water-to-air heat pump, air-to-air heat pump), high-temperature radiant/convective units (baseboard, radiators) and low-temperature radiant panels. Users must specify equipment in the order it will be used to meet zone heating and cooling demand.

There are two loops for HVAC plant equipment, a primary loop (for supply equipment such as boilers, chillers, thermal storage, and heat pumps) and a secondary loop (for heat rejection equipment such as cooling towers and condensers)

3-5 Statistical analysis generator;

3-5-1 Overview;

The analysis generator translates the simulation results into statistical relations and charts, which help designers make the decisions related to the actual contributions of the building components on energy consumption. The designer can select the design variables, the statistical analysis type, and the data output chart forms, which will be included in the analysis.

The analysis generator in the evaluation model accesses both the design solution input files and the building performance simulation tools output files. The performance of the different design solutions, which is obtained from the simulation is analysed at this stage by Microsoft excel 2000© statistical analysis package (figure 3-6). The analysis generator generates the required statistical relations between the building component variables and its effect on the building energy performance. The analyses generator also plots the relations between the different design components and the resulting performance in two and three-dimensional charts.

3-5-2 Design variables;

In this stage, the designer selects the design variables of interest, which will be included in the statistical analysis. In order to obtain sound statistical relations between these design variables, it should have a practical range of values. These design variables may include the following;

- Building formation, building volume, and wall areas.
- Window areas, locations, and shading coefficient.
- Daylighting .
- Electrical lighting use factor, and efficiency.
- Mechanical system selection, and performance.
- Pollution and noise control.
- Indoor air quality.
- Comfort level parameters.

Since the scope of this research is limited to investigating the contribution of thermal mass, thermal insulation, solar radiation and natural ventilation, the evaluation model will generate statistical relations between only these design variables.

3-5-3 Statistical analysis types:

The designer can select the statistical analysis methods which will derive the required relations between the building alternatives and its effect on the building thermal performance. The statistical analysis generator carries out basic statistical analyses through Microsoft excel 2000©. These analyses include calculation of the minimum value, maximum value, average value, standard deviation, and count. In addition, the analyses generator performs advanced statistical analysis which include the following:

1- Correlation analysis; which obtains correlation coefficients between the selected

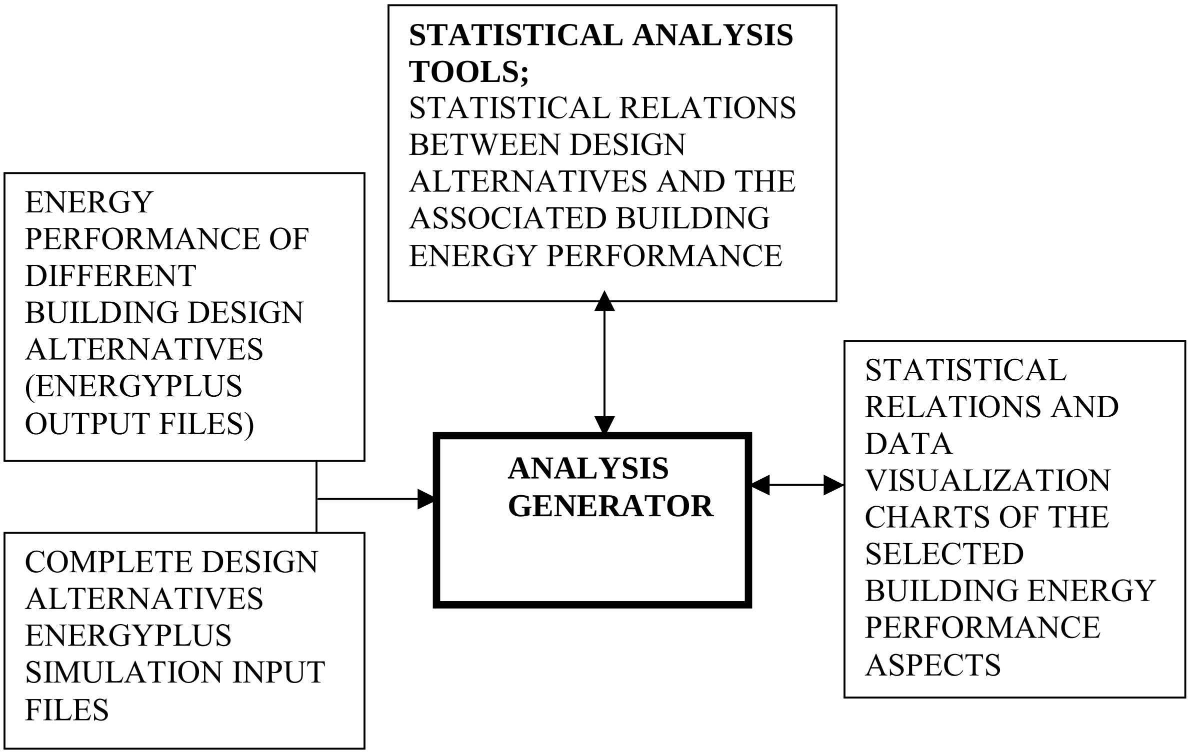


Figure 3- 6: Building analysis Generator

design variables and the building thermal performance.

2- Linear regression analysis: the designer may carry out single and multi-variable regression analysis .

3- Nonlinear regression analysis: which allows the designer to derive different levels of mathematical relations such as square, third power, and logarithmic relations.

4- ANOVA table: The analysis of variant tables gives designers a wide picture of the effect of the selected design variables on the building energy consumption. The ANOVA table includes the sum of squares, mean square error, hypotheses testing, probabilities, r^2 (mean square error), line intercept, line slope, standard error of line intercept and line slope. Other advanced statistical relations such as generic algorithm and neural network can also be obtained. However, these relations are beyond this research scope.

3-5-4 Data visualization;

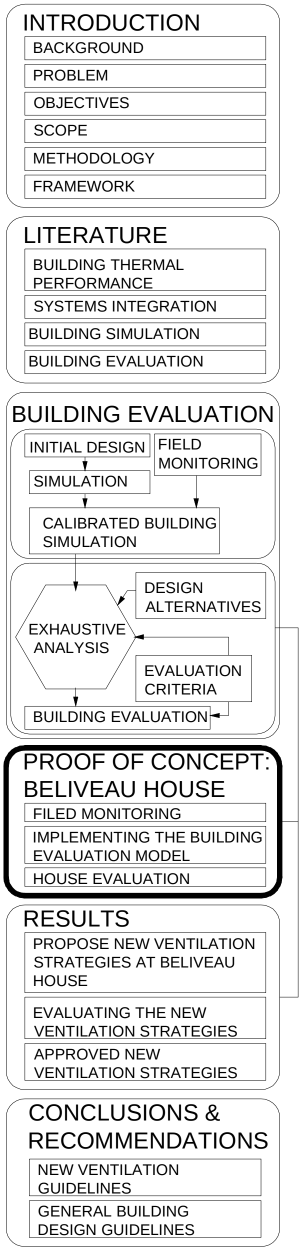
Data visualization is as important as mathematical relations in presenting building thermal performance. The analysis generator can produce different types of charts, which show the relationships between the design variables and the associated heating and cooling load. These charts include X-Y scatter plots, smooth line plotting, area plotting, 3D charts, and bar charts.

The data visualization window helps the designer to visualize complex relations between the building design variables and help in taking the appropriate design decisions. Other advanced data visualization techniques such as multi dimensional data visualization can also be incorporated, but they are beyond this research scope.

Finally, this evaluation model will from the base for a comprehensive building evaluation methodology, which is hoped to cover all the building design aspects.

Chapter Four

IV: PROOF OF CONCEPT



IV. Proof of concept;

4-1 Overview;

In order to test the proposed evaluation model, a field study and computer simulation were conducted on the Beliveau House in Blacksburg, Virginia. The house designer Prof. Yvan Beliveau implemented several energy conserving ideas such as passive solar radiation, thermal mass, thermal insulation, and air ventilation. The evaluation model was used to investigate the relationships between the main building design variables and their contribution to energy consumption in the house. These relationships were also used to predict the best ventilation strategies that reduce sensible and latent heat load.

The house was first simulated using EnergyPlus©. The simulation results were validated with the field readings. Second; the evaluation model was used to generate a matrix of alternative solutions with different building mass levels, solar radiation gains, and thermal insulation factors. Third the design solutions were simulated using the evaluation model and the EnergyPlus© software. Finally, the evaluation model was used to derive the statistical relations between the energy consumption (as dependent variable) and the solar radiation, thermal insulation, and building mass (as independent variables).

4-2 Building selection justification;

The Beliveau House were selected to validate the proposed evaluation model, test the integration of thermal mass, thermal insulation, solar radiation air ventilation, and to investigate the potential energy savings while implementing new ventilation strategies.

The following criteria were considered in selecting the Beliveau House for the field-testing;

1. The Beliveau House is a unique passive solar house, where the energy conservation was not the only design goal. The designer implemented the concept of systems

integration. The designer's concern was to select the building systems that might achieve designer goals as these relate to the holistic design aspects, which includes the selection of the finish materials, structure, daylighting, air quality, space quality, as well as energy conservation. The designer based his energy conservation strategies on controlling the direct solar gain, increasing the floor thermal mass, optimizing the amount and location of thermal insulation, utilizing natural ventilation, and heat recovery through air-to-air heat recovery system. The designer based his decisions on his experience in the different design fields.

2. The house is occupied by Prof. Beliveau, the designer of the house, hence the house operation is sensitive to energy conservation, and facilitates the house monitoring under different cooling and heating strategies. The Beliveau family also lives in the house, which insures typical house operation.
3. Mrs. and Mr. Beliveau offered their house for monitoring and installing the required sensors in the house. They also offered a space to place the computer and the data acquisition equipment in the house, and provide access to the data acquisition system throughout the monitoring period.
4. The house is located in a climate region, which has overheating, and underheating periods. This region also experiences both high humidity, and low humidity periods, clear and cloudy sky conditions. This climate condition is an ideal field test for this research.
5. The house is located in a countryside, which has minimum impact from the urban surrounding, and allows for implementing the natural ventilation strategies without air pollution restrictions. In addition, the house location is not affected by other built environment surrounding.
6. The designer and his family built this house by themselves, which ensures the true implementation of the desired concepts, and it provided the researcher with accurate description of the house construction, and the concepts behind the building design and construction ideas.

4-3 Description of the house;

The Beliveau house is located in the countryside of Blacksburg, Virginia, at latitude of 38 degree and an altitude of approximately 750 m above the sea level. The total living floor area of the house is approximately 580 m ² (Figure 4-1). The climate in this area is warm and relatively humid in summer, and cold in winter (Figure 4-2).

The house consists of three levels; the main level contains the living space, kitchen, dining room, family room, and a bedroom; the lower level contains bedrooms and recreation rooms, and the upper level contains the master bedroom suite and office space (Figure 4-3) (Figure 4-4).

Figure 4- 1: The Beliveau house south elevation

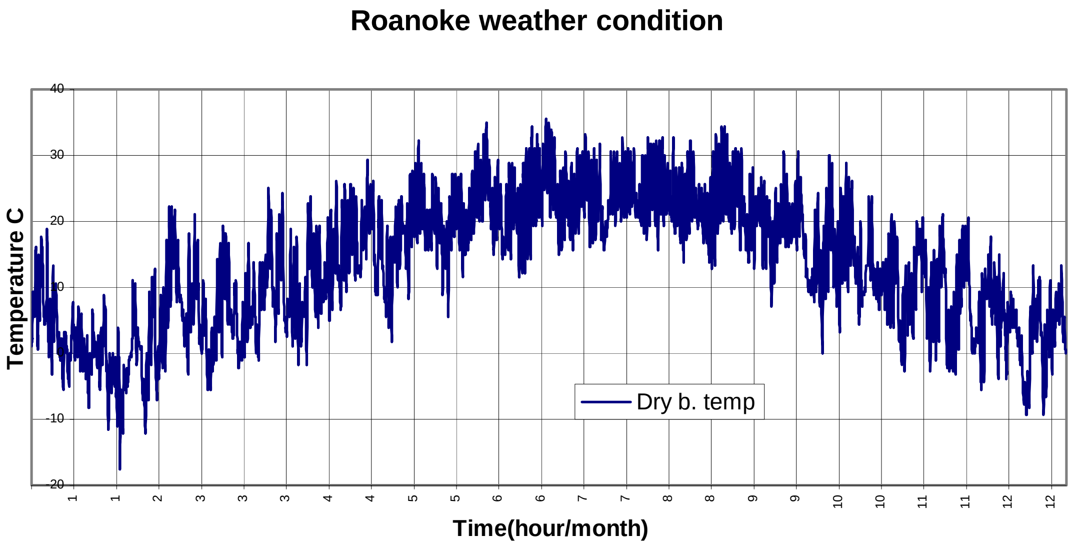


Figure 4- 2: Weather condition in Roanoke area (Source: TMY weather file)

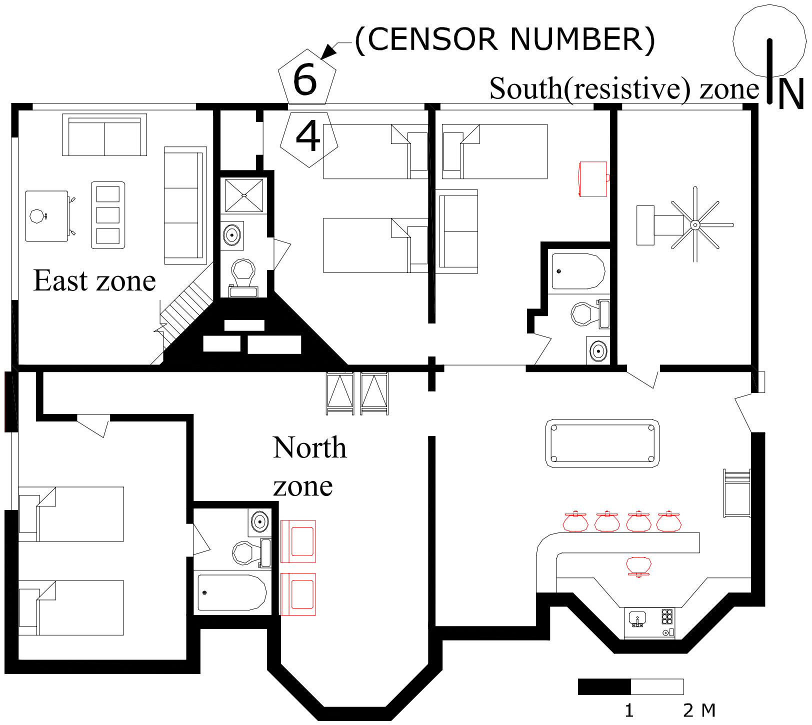


Figure 4- 3: House basement floor plan.

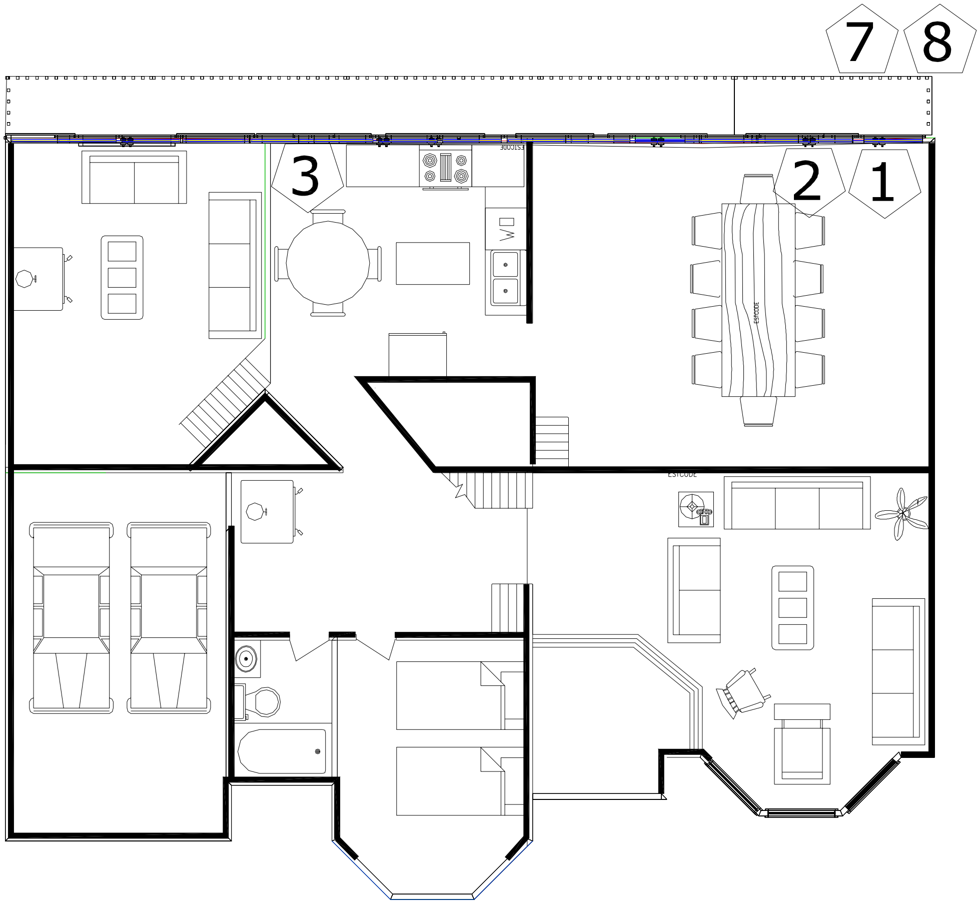


Figure 4- 4: House first floor plan.
and the thermocouple locations.

The house site slopes 4 m (20%) from the north towards the south. The house was designed to fit into the existing topography. The designer took advantage of the sloped site and placed part of the house basement below grade level. Deciduous trees were used to shade the east elevation, and part of the west elevation. These trees provide shading for the structure in the summer time and exposed it to the winter sun. The outside green areas and swimming pool were also located in the house south side (figure 4-1).

The main construction material of the house is wood. The walls are composed of 13mm wood cladding from outside, glass fibre insulation faced with building paper (U value = .3 W/m².C°) , and 13mm sheet rock board on the inside (Figure 4-5).

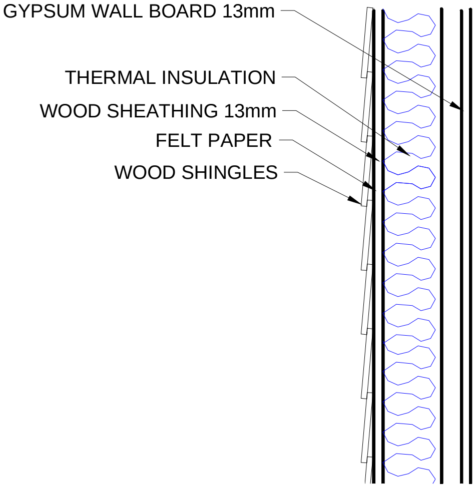


Figure 4- 5 ; Typical wall construction at the Beliveau house.

The floor of the main level is constructed of a composite concrete and wood structure. It consists of 20mm plywood and 75mm fibreglass reinforced concrete slab connected to 50 x 250 mm wood joists (Figure 4-6). The main objective of this slab is to provide thermal mass inside the house, and to provide a suitable surface for installing dark ceramic floor tiles, which is facing the south facade, in which the most house glazing area is located. The designer intention was to make the floor an energy absorber from the passive solar south window.

The windows are medium emittance double-glazed with a 28mm air cavity and adjustable bronze blind inside the cavity (figure 4-7). These windows can control the amount of solar radiation.

The roof is composed of two layers separated by a ventilated cavity. The top layer is composed of black asphalt shingles placed over 13mm plywood. The inside layer consists of fibreglass thermal insulation with U-value equals 0.5 W/m².C°, and 18mm wood board or 13mm sheet rock (Figure 4-8).

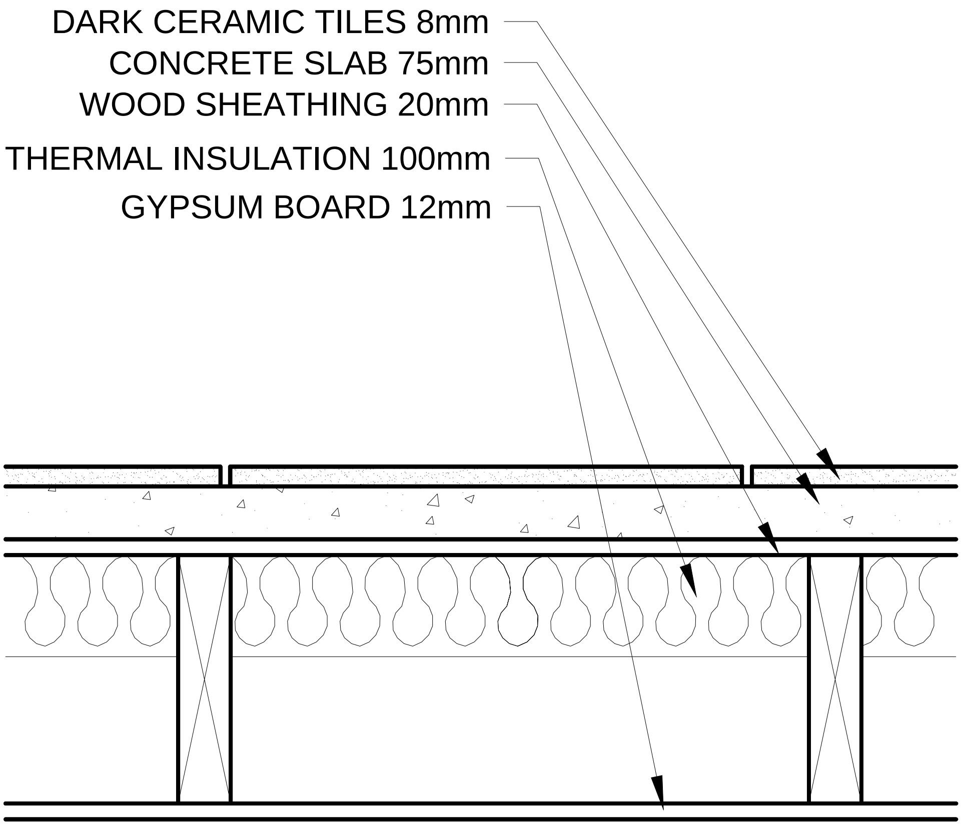


Figure 4- 6; First floor construction at the Beliveau House.

Which faces the south façade in the first floor

The house has a ventilation system which is separated from the house air conditioning system. The ventilation system exhausts the air from the bathrooms and the kitchen, and admits fresh air through an air-to-air heat exchanger with 70% heat recovery. The fresh air is distributed through separate exhaust duct system. The windows allow for cross ventilation when outside conditions permit (Figure 4-9).

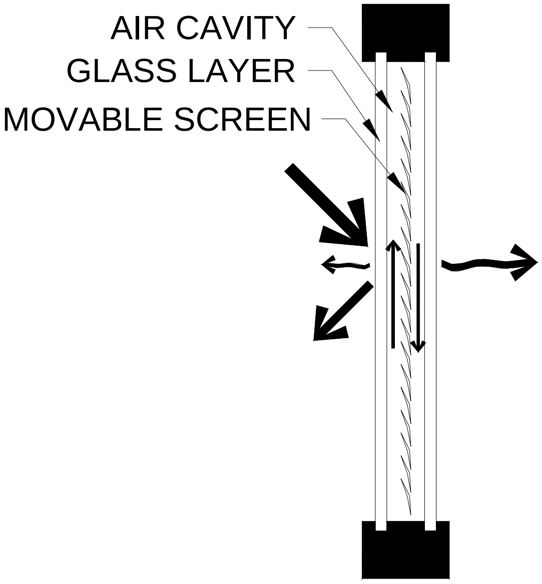


Figure 4- 7: South window at the Beliveau house.

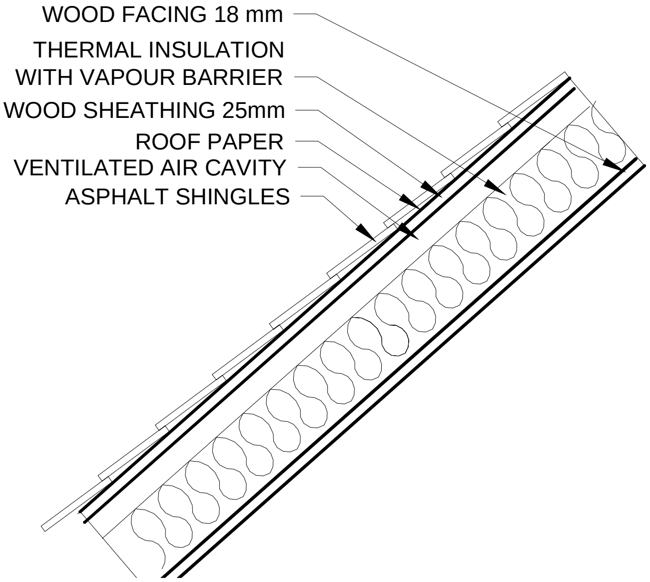


Figure 4- 8: Roof construction at Beliveau house.

4-4 Implementing the evaluation model;

The evaluation model was used to predict the effect of the thermal mass, solar radiation, and thermal insulation on heating and cooling loads. First, the current house construction is used as a base case. The base design was simulated and calibrated against field monitored data. Second, the evaluation model generated alternative solutions with different thermal mass, thermal insulation and solar radiation gain. Third, statistical relations were obtained to explain the contribution and interaction between the these variables and energy consumption.

4-4-1 Base design;

The house was simulated in its current construction. The simulation software which is used to simulate the house was tested and calibrated against the field readings as was discussed earlier in this chapter. This house simulation was used as a base design. Several assumptions were made to provide a full representation of the house. These assumptions are as follows:

4-4-1-1 Weather condition;

The weather data of Roanoke city at Virginia were used in simulating Beliveau house. This weather station is the closest to Blacksburg, the location of our case study.

Although the micro-climate conditions have considerable effect on the house simulation results, it was difficult to obtain full weather data at the house location. However, some of the micro-climate conditions such as the actual solar radiation were obtained from the field readings, and considered in calibrating the window performance of the base design. The actual wind speed in the site was also considered when specifying the house level of exposure.

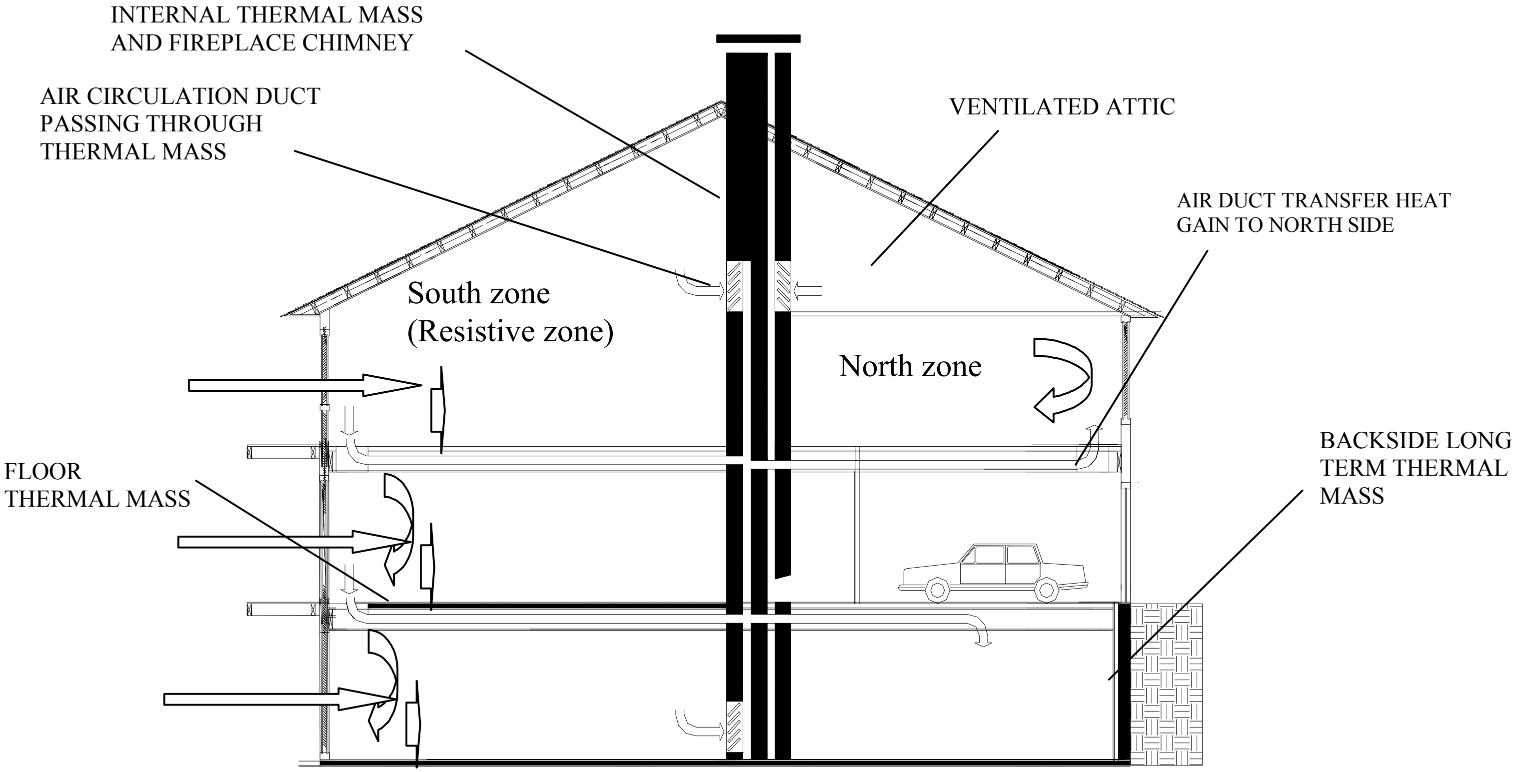


Figure 4- 9; Cross section of the Beliveau House.

4-4-1-2 Building materials;

Specifying the building materials in existing buildings requires estimations and assumptions of some of the building materials properties such as the concrete density, inside and outside building surfaces reflectance, windows solar transmittance, and outside air infiltration. (Appendix 2). These estimations were tested and calibrated against the field monitoring as will be discussed later in this chapter.

4-4-1-3 Building operation;

The occupant's number in the house was assumed 3 persons. The air conditioning running schedule was set to continuous operation for the fan coil, and a load only operation for the heat pump. The air ventilation rate was set to a minimum10 liter/second for each house occupant. The heating demand of the hot water was not included in the house simulation. The other house internal load was scheduled to a maximum of 5Kw per day. Appendix 2 page shows the building operation schedules.

4-4-2 Field test;

The objectives of the field test are to examine the actual performance of the house under different climate conditions, and to calibrate the simulation model. Locations of the climate sensors are shown in (Figure 4-3) (Figure4-4) and are further described below:

1. The first thermocouple was installed on the first floor space and at a height of 1m. This sensor measured the main living space air temperature. The data obtained from this sensor was used to calibrate the inside comfort parameters in the simulation model under the active mode, and to calibrate the overall house performance under the passive mode.
2. The second thermocouple was located on the interior glass surface of the southern window at a height of 1m to measured the internal glass surface temperature in the

main space. This sensor was used to calibrate the simulation of the direct solar radiation gain through the south glazing area.

3. The third thermocouple was installed in the air-conditioning outlet at the first floor. This sensor was used to predict the overall air temperature of the house when the house is running in a passive mode, and to predict the air-conditioning running time in the active mode. This sensor was also used to estimate the current active heating and cooling load in the house.
4. The fourth thermocouple was placed on the south wall of a basement bedroom. It was used to measure the air temperature variation in the different house locations.
5. The fifth thermocouple was installed on the kitchen wall. Which was also used to measure the air temperature variation in the different locations of the house.
6. The sixth thermocouple was placed outside the house on the south façade to measure the outside air temperature.
7. A solar radiation sensor was installed on the house southern façade on the first floor level. This sensor was used to measure the direct solar radiation.
8. An air velocity sensor was installed near the south west corner of the house at 1m above the level first floor. It was used to calibrate the weather data and to determine the house weather exposure level.

   The wind sensor, the solar radiation sensor, and the outside thermocouple were used to calibrate and modify the weather data, which was used in the house simulation in order to account for the house site microclimate, and to calibrate the house simulation.

All the sensors were connected to a 21X data recorder. The data recorder stored and transferred the collected data to a computer, which was used to monitor and store the data. The data acquisition system was set to record the maximum and the average reading of the eight environmental sensors every five minutes. The data acquisition system was installed at Beliveau house between April and October 1998.

The collected data was categorized into overheating periods, and under heating periods. The over heating periods were also categorized into periods where cross ventilation was used and to periods where mechanical ventilation was used.

4-5 Simulation model calibration;

As we discussed early in the literature review, predicting building energy performance is complex and requires several assumptions and generalizations. Although many researchers based their prediction of building performance solely on computer simulation (Simmonds, 1991), Feustel (Feustel, 1992), computer simulation may not truly represent the actual building performance.

To accurately simulate the energy performance of the Beliveau house, the simulation results were compared to the field readings.

Previous research by Judkoff (Judkoff, 1994) and Dickson (Dickson, 1996) suggested that testing the simulation results against the field data for a period of 7-15 days of the tested period is reasonable for calibrating the simulation results. It should be pointed out that the scope of the house field monitoring was not to validate the accuracy of EnergyPlus, but to calibrate the Beliveau house energy simulation.

The computer simulation was tested and calibrated against the field readings. The following simulation routine was calibrated against the field readings:

4-5-1 Direct solar radiation;

EnergyPlus© simulates the direct and indirect solar radiation gain through windows. It also calculates the surface temperature of the window layers under steady state. Since the time lag of the window construction is relatively short (30minutes), to calibrate the simulation of the solar radiation gain, the weather data file in the simulation was modified to match the field solar radiation levels at certain periods of time. The outside air temperature in the simulation software weather data was also modified to match the measured outside air temperature at the house. The field readings of the inside surface temperature of the window glass was compared to the surface temperature of the same glass layer which is obtained by the simulation results.

Calibration and adjustment to the glass properties were also made to match the simulation results with the field readings.

4-5-2 Define the inside comfort condition;

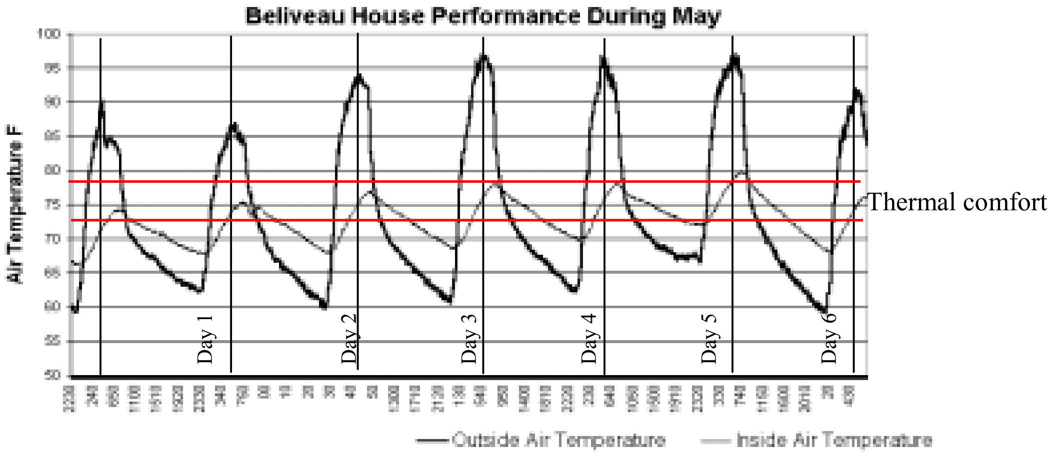
Comfort parameters set points have significant impact on heating and cooling load, the average mean minimum and the average mean maximum inside air temperature obtained from the field monitoring were 65 to 78 F(18-26 C°). This air temperature range was used as a set point temperature in the simulation software. The maximum relative humidity of 60% were also set as a comfort parameter.

4-5-3 Overall building performance under passive mode;

The main construction material of the Beliveau house is wood, and the house can be considered of medium weight construction, therefore, the time lag and the house sensible thermal storage is medium. Thus, a 7-day calibration time is reasonable for such buildings.

A set of 7 consecutive days of similar outside weather condition and inside comfort level were selected from the field data to represent the house performance in moderate days, hot days, and cold days (Figure 4-10) (Figure 4-11) (Figure 4-12) (Figure 4-13).

Each of these sets of days were also averaged to represent a typical one-day energy performance of the house in each of the above weather situations. Then, the building simulation was calibrated to match each of the above sets of weather condition. The field readings of the inside air temperature at each of the above weather conditions were matched to the inside air temperature obtained by the house simulation (Figure 4-14).



Time 5min.
intervals

Figure 4- 10: Passive building performance in moderate days

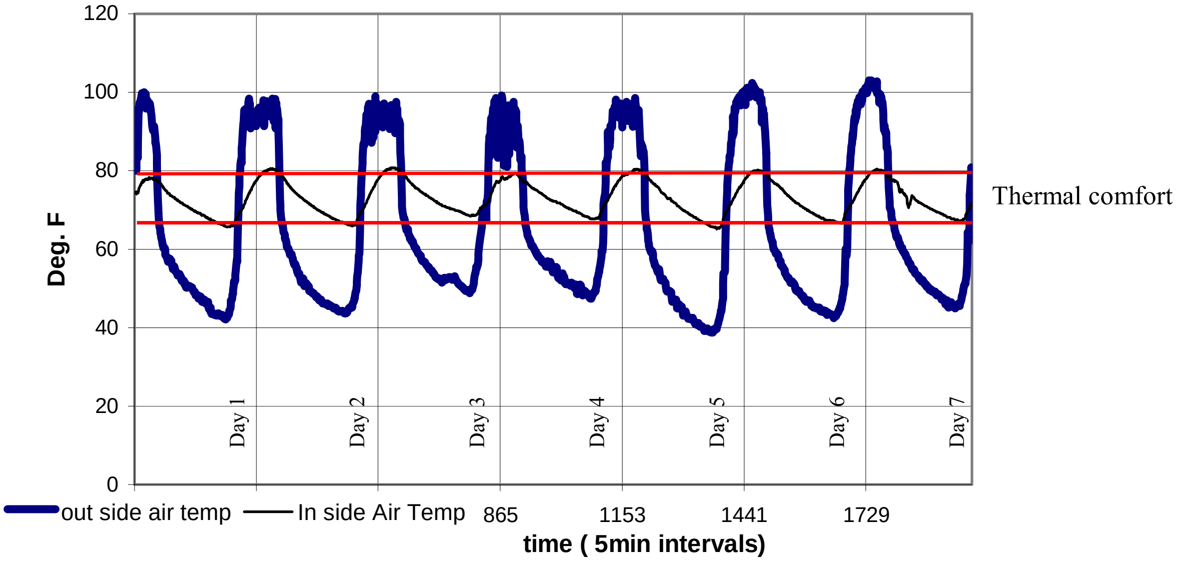


Figure 4- 11 : Passive building performance in cold nights and warm days

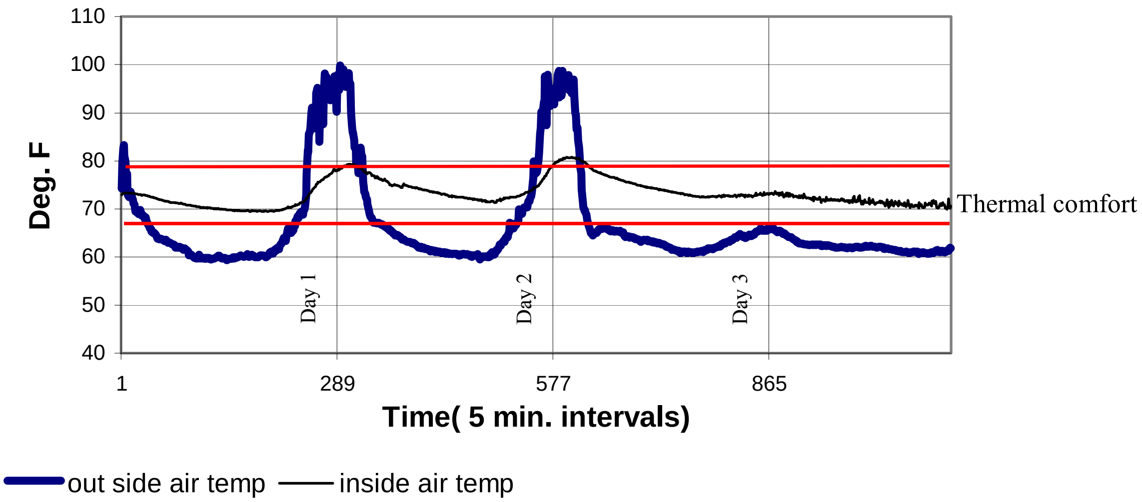


Figure 4- 12 ; The house performance in cold days after hot days

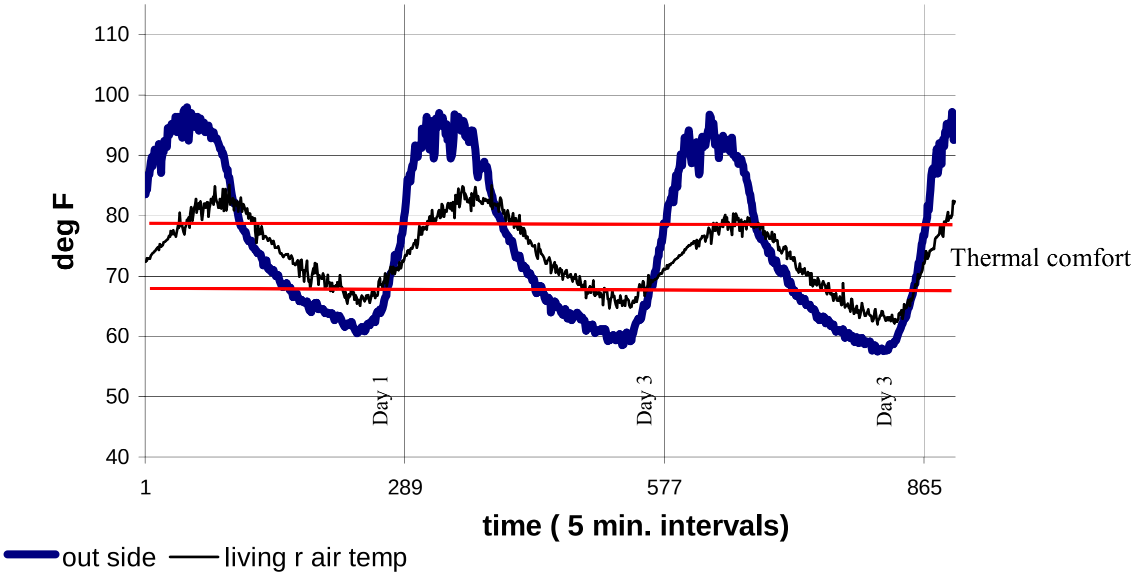


Figure 4- 13; Passive house performance during hot periods with natural ventilation at night.

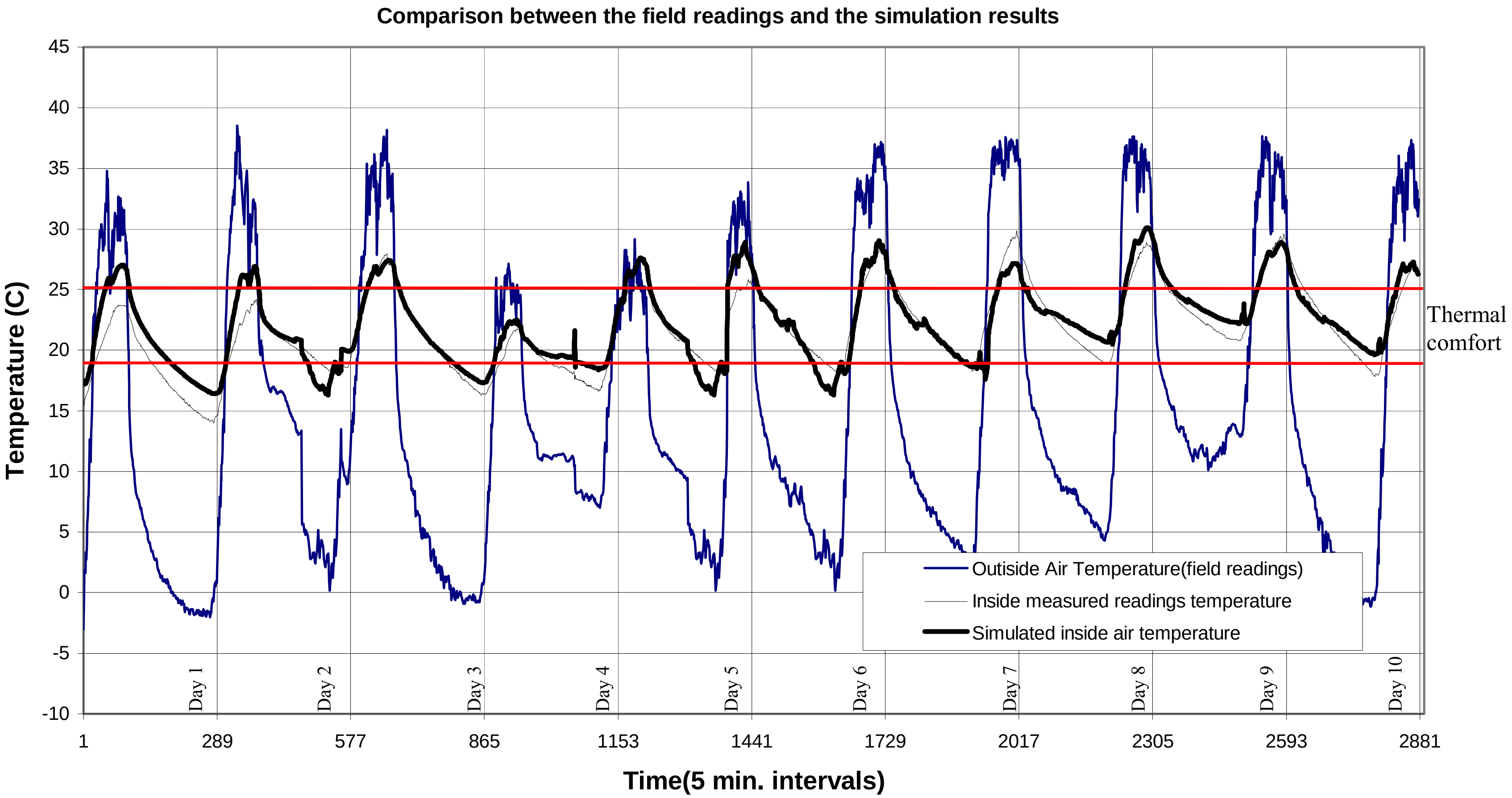


Figure 4- 14; Comparison between the field readings and the simulation results at Beliveau House

Statistical analysis was carried out between the field-measured readings and the simulation results of the inside air temperature. The correlation coefficient between the predicted air temperature inside the house and that of the field readings was .93, and the standard deviation between the predicted air temperature inside the house and that of the field readings was 3.31.

A regression analysis was also carried out between the predicted inside air temperature and the field measured inside air temperature (Table 4-1) (Figure 4-15) (Figure 4-16). The relation between the predicted inside air temperature (PT) and the field measured air temperature (FT) can be presented as follows;

PT=-.639+.947 FT.

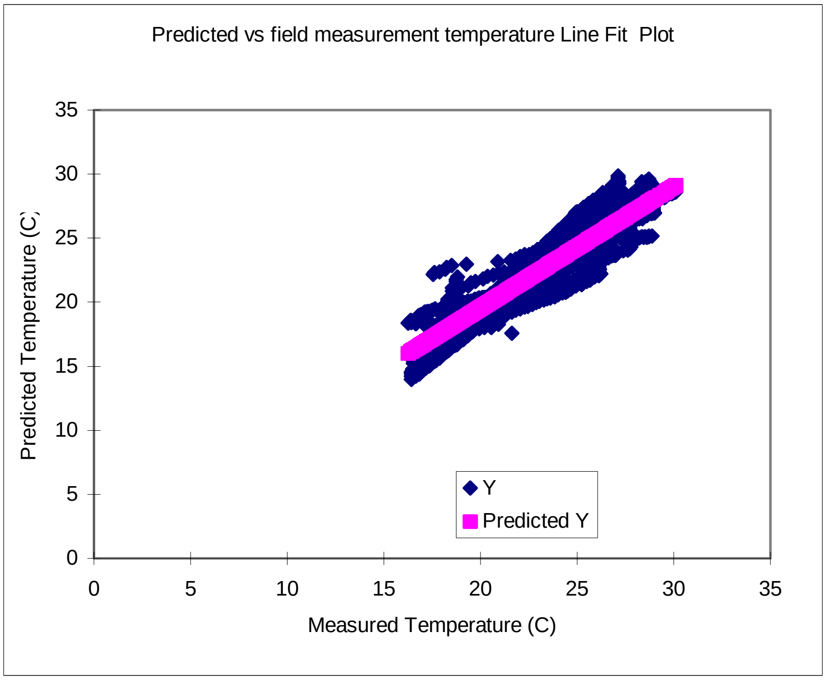


Figure 4- 15: Line fit of air temperature predicted versus the actual values.

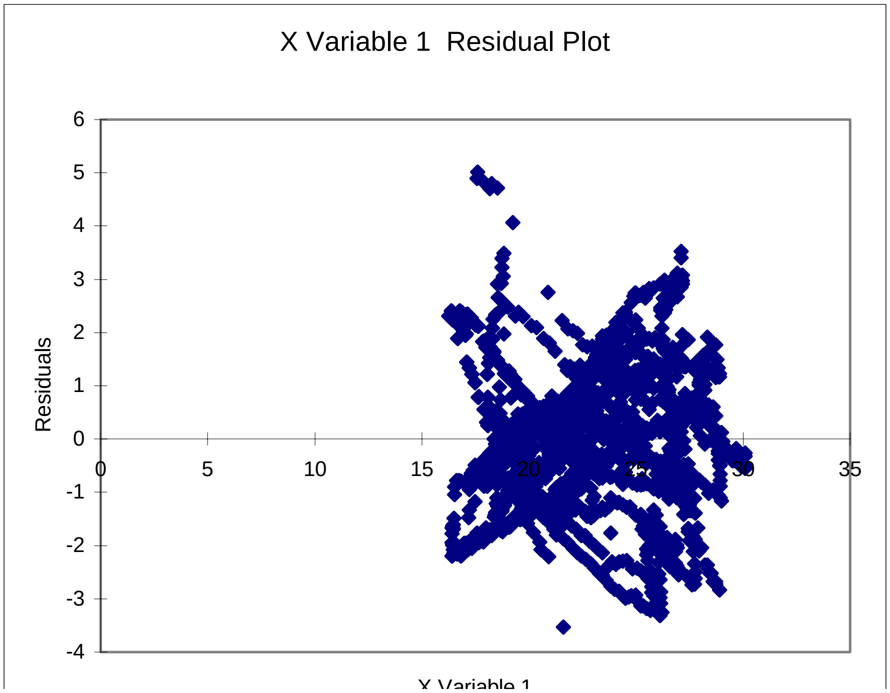


Figure 4- 16: Residual plot from regression relation of predicted versus actual air temperature .

Table 4- 1: Regression analysis results of predicted versus actual air temperature of the Beliveau House in moderate days.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.937117377
R Square	0.878188978
Adjusted R Square	0.878146623
Standard Error	1.156115874
Observations	2878

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	27713.60376	27713.6	20734.34283	0
Residual	2876	3844.072855	1.336604		
Total	2877	31557.67662			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.555531538	0.156186167	-3.55685	0.00038138	-0.861779613	-0.249283462
X Variable 1	0.995127567	0.006910884	143.9942	0	0.981576783	1.008678351

4-5-4 Building performance under active mode;

To monitor the air conditioning runtime of the Beliveau house, a thermocouple was installed in the air supply duct. Under the active mode, the house simulation was also calibrated for seven days. The total heating and cooling load of the simulation were matched with the measured active heating and cooling load in the house.

4-6 House performance;

The field readings showed that the house was within the comfort zone for 72% of the hours during the tested period without using the active heating or cooling. The major cooling strategy in the house was the integration of the thermal mass, controlled solar radiation, and the controlled natural ventilation. The house was ventilated at night to flush the excess heat. The thermal mass absorbed the heat from the space during the hot periods and balance the daily inside air temperature fluctuations (Figure 4-12). The maximum benefit of the thermal mass was when a heat front proceeds cool days, or a cool front proceeds hot days (Figure 4-13).

The house heating strategy is based on utilizing the direct solar radiation admitted to the space and absorbed by the thermal mass; this heat is re-radiated to the space when the space cooled down. The heat exchanger played a major role in providing ventilation of .75 air changes per hour while it recovered 70% of the energy loss through ventilation in both the heating and the cooling periods.

The house energy performance simulation showed that the yearly electric consumption for heating is approximately 8000kW, and the electric consumption for cooling is 2560kW. The simulation results of the house performance in its current situation were as follows;

The total solar radiation admitted to the house through the year was 16813 kW (11080 KW in the heating periods and 5731 kW in the cooling periods). The total heat gain and loss through the building envelope other than direct solar radiation was 24887 kW (23652 kW heat loss in the heating period, and 1234kW heat gain in the cooling period).The total heating and cooling load was 15434 kW. The difference between the total heat gain/loss through building envelope and actual heating and cooling load of

4103 kW (21% of the heating and cooling load) .This load was balanced as a result of the thermal mass in the house.

In percents: the solar radiation for the entire year factored 31% of the energy load of the house ((16813/(16813+24887) X 79%), while the building envelope factored 48% of the energy load ((24887/(16813+24887)X 79%) .

4-7 Implementing the evaluation model;

To test the effect of thermal mass, thermal insulation, solar radiation, and natural ventilation on the Beliveau house thermal performance, the house was simulated in its current construction. Second, the house construction was modified to match the conventional construction of similar buildings; the concrete floor was replaced with conventional wood floor without thermal mass, the existing windows were replaced with ordinary double glazing window, the natural ventilation was deleted and the house was run as a closed envelop.

Under the second case, where the house construction was modified to match conventional construction, the house performance showed that the total heating load is approximately 44000 kW, and the total cooling load 13100 kW per year.

4-7-1 Generating alternative building solutions;

To test the contribution of thermal mass, thermal insulation, and solar radiation on the house energy consumption, the house was simulated with different glass heat transmittance, wall thermal insulation, and concrete floor thickness.

A matrix of five different values of each of the above variables was used to generate design alternatives (Table 4-2). The solar radiation gain alternatives were achieved by setting the south windows glass shading control at 0-30W/m² The thermal insulation alternatives were achieved by setting the external walls U-values range between .23W/m² and 1.1W/m², and the thermal mass alternatives were achieved by setting the concrete floor slab thickness range between 0 and 6 inches. These ranges of building variables were chosen based on practical, economical, and aesthetic considerations.

Based on this matrix of alternative building components, the solution generator in the evaluation model generated 216 complete solution files in order to feed the simulation generator.

Table 4- 2: Thermal mass, thermal insulation, and solar radiation alternatives which is used in evaluating the Beliveau house.

Matrix of alternative solutions used to derive relations between thermal mass, thermal insulation, solar radiation and building thermal load								
Glass Transmittance (%)	Exterior envelope U value (w/m2)	Concrete Floor Thick (mm)	Glass Transmittance (%)	Exterior envelope U value (w/m2)	Concrete Floor Thick (mm)	Glass Transmittance (%)	Exterior envelope U value (w/m2)	Concrete Floor Thick (mm)
10	0.23	0						
10	0.5	0	20	0.23	0	20	0.5	0
10	0.9	76.2	30	0.23	76.2	30	0.9	0
10	1.3	114.3	40	0.23	114.3	40	1.3	0
10	1.7	152.4	50	0.23	152.4	50	1.7	0
20	0.23	0	10	0.5	0	10	0.23	38.11
20	0.5	0						
20	0.9	76.2	30	0.5	76.2	30	0.9	38.1
20	1.3	114.3	40	0.5	114.3	40	1.3	38.1
20	1.7	152.4	50	0.5	152.4	50	1.7	38.1
30	0.23	0	10	0.9	0	10	0.23	76.2
30	0.5	0	20	0.9	0	20	0.5	76.2
30	0.9	76.2						
30	1.3	114.3	40	0.9	114.3	40	1.3	76.2
30	1.7	152.4	50	0.9	152.4	50	1.7	76.2
40	0.23	0	10	1.3	0	10	0.23	114.3
40	0.5	0	20	1.3	0	20	0.5	114.3
40	0.9	76.2	30	1.3	76.2	30	0.9	114.3
40	1.3	114.3						
40	1.7	152.4	50	1.3	152.4	50	1.7	114.3
50	0.23	0	10	1.7	0	10	0.23	152.4
50	0.5	0	20	1.7	0	20	0.5	152.4
50	0.9	76.2	30	1.7	76.2	30	0.9	152.4
50	1.3	114.3	40	1.7	114.3	40	1.3	152.4
50	1.7	152.4						

4-7-2 Simulating the building alternatives;

The simulation generator loaded the solutions which were generated by the solution generator, runs them in the simulation engine, and saved the simulation output files into Microsoft Excels format. An input interference was necessary at some simulation stages to complete the simulation and save the simulation output files. However, fully automating the multi-simulation requires programming solutions, which are beyond this research scope.

4-7-3 Evaluation results;

The house performance under different amounts of thermal mass and thermal insulation, different solar radiation control, and different ventilation rates were as follows;

4-7-3-1: Thermal insulation;

If the current as-built level of thermal mass and solar radiation were maintained, and the nighttime ventilation was not utilized, changing the thermal insulation thickness in the roof and the walls from 20mm to 100mm (U value of 0.23 - 1.1 W/m².C°) would reduce the heating load and cooling load of the house by 47% .

Furthermore, if the roof and the walls thermal insulation U-value 0.23 W/m².Cº (100mm rigid insulation), the house would maintain a comfortable air temperature for 72% of the year in the south wing, 66% in the east wing, and 69% in the north wing (Figure 4-17)(Table 4-3). Appendix 1 presents the house performance under different thermal insulation values.

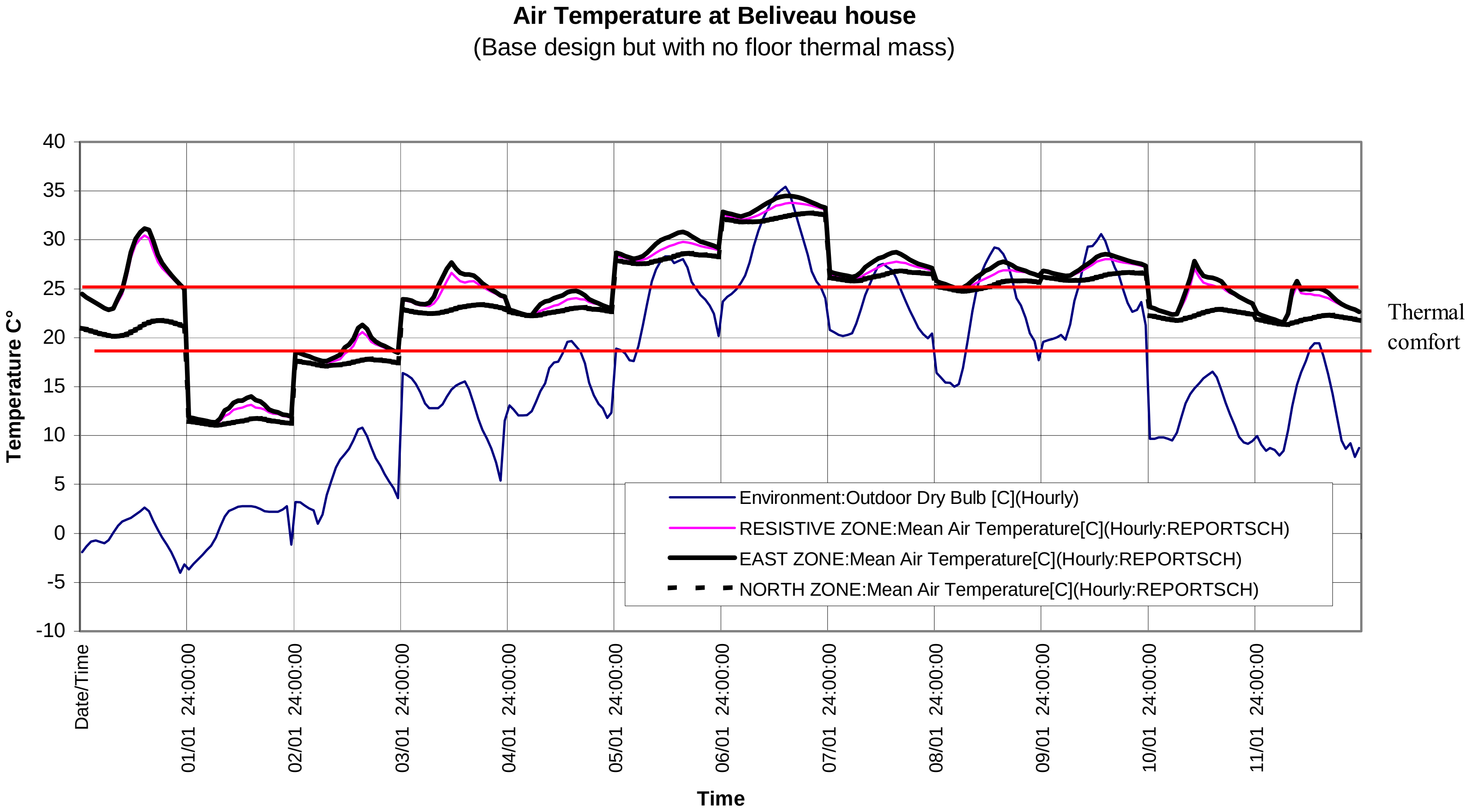


Figure 4- 17: House performance with walls and roof insulation = 0.23W/m².C°.

4-7-3-2: Thermal mass;

If the current level of thermal insulation and solar radiation were maintained, and the nighttime ventilation was not utilized, changing the house concrete floor slab thickness from 0 to 200mm would reduce thermal load of the house by 21%. However, thermal mass showed significant impact on increasing the time where comfort air temperature was achieved. With no concrete floor slab, the house maintained a comfortable air temperature for 49%, 44%, and 63% of the year in the south, east and north zones respectively (Figure 4-18) (Table 4-4).

Under the same conditions the house simulated with a 200mm thick floor slab, the house maintained a comfortable air temperature for 75%, 67%, and 83% of the year in the south, east and north zones respectively (Table 4-5) (Figure 4-19). These results showed that although the thermal mass has little effect on the thermal load, it has significant effect in increasing the time where air conditioning is not required. We may also notice that most of the comfortable air temperature increase was in the cooling period. These results suggest that the air conditioning system will run less when the house has the floor thermal mass, which is vital for enjoying the beauty of the passive cooling.

Table 4- 3 : House performance with walls and roof insulation = .23W/m².C°

	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26 C	46.00	58.00	73.00	42.00
Number of Under Heating Hours with temperature<18 C	162.00	24.00	24.00	48.00
Total Number of Hours simulated	288.00	288.00	288.00	288.00
percent of over Heating hours %	15.97	20.14	25.35	14.58
percent of under Heating hours %	56.25	8.33	8.33	16.67
percent of comfortable air temperature hours %	27.78	71.53	66.32	68.75

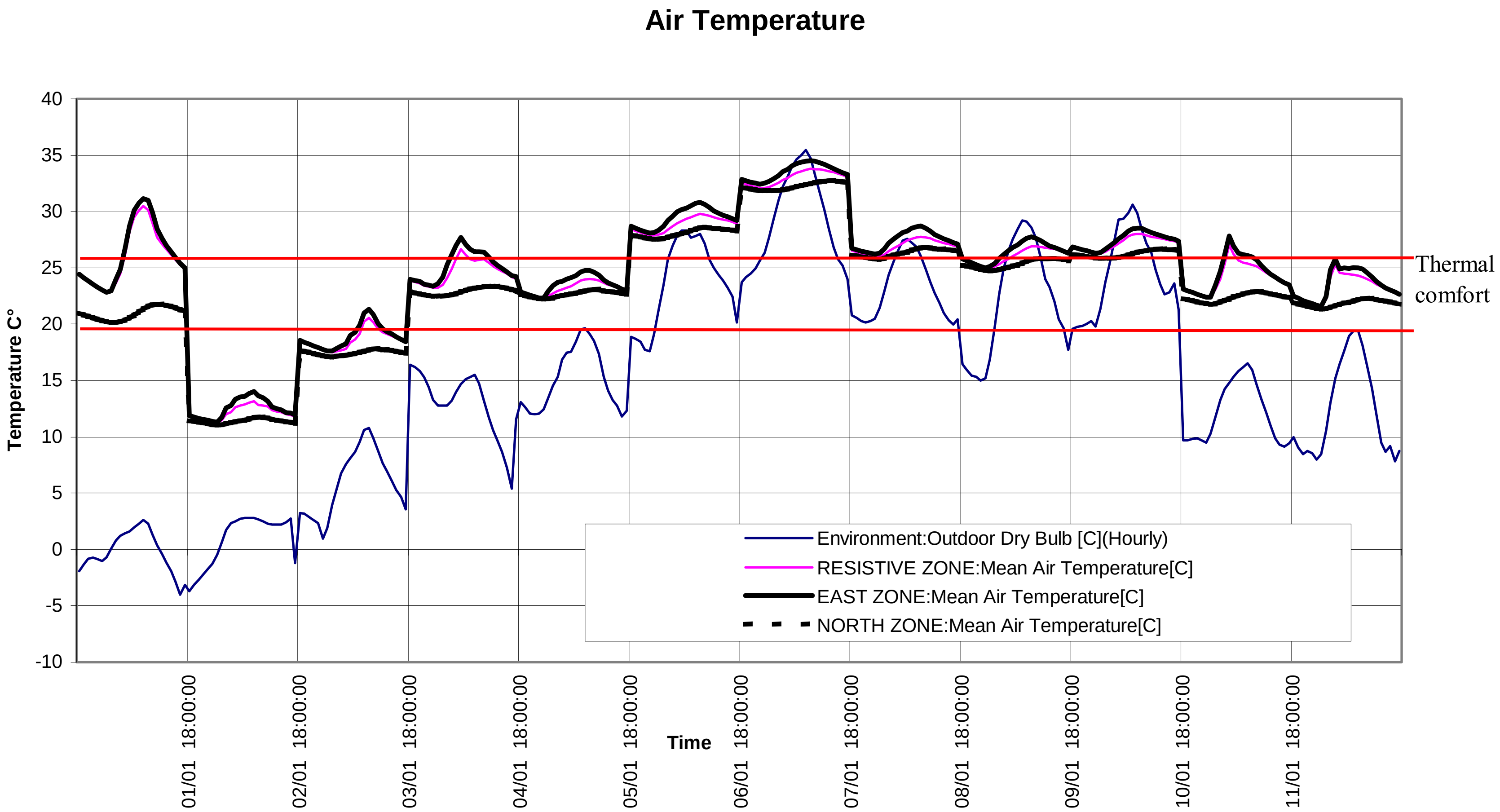


Figure 4- 18; Beliveau house performance with no floor mass.

Table 4- 4 : Beliveau house performance with no floor mass.

	Environment	SOUTH ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26 C	46.00	124.00	136.00	83.00
Number of Under Heating Hours with temperature<18 C	162.00	24.00	24.00	24.00
Total Number of Hours simulated	288.00	288.00	288.00	288.00
percent of over Heating hours %	15.97	43.06	47.22	28.82
percent of under Heating hours %	56.25	8.33	8.33	8.33
percent of cofortable air temperature hours %	27.78	48.61	44.44	62.85

Table 4- 5; House performance with 200mm thick floor mass.

Date/Time	Environment	SOUTH ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26 C	46.00	49.00	71.00	26.00
Number of Under Heating Hours with temperature<18 C	162.00	24.00	24.00	24.00
Total Number of Hours simulated	288.00	288.00	288.00	288.00
percent of over Heating hours %	15.97	17.01	24.65	9.03
percent of under Heating hours %	56.25	8.33	8.33	8.33
percent of cofortable air temperature hours %	27.78	74.65	67.01	82.64

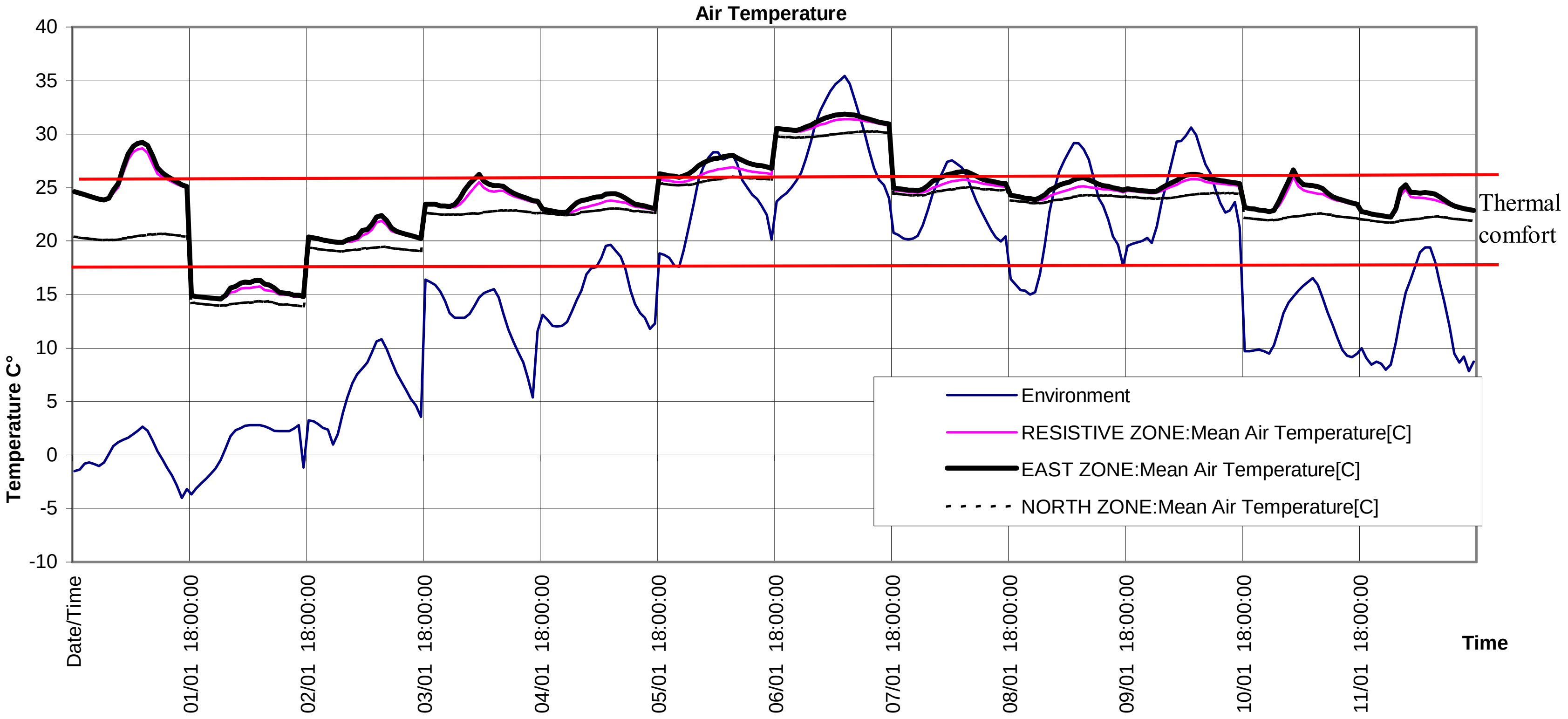


Figure 4- 19: House performance with 200mm thick floor mass.

4-7-3-3: Solar radiation;

The simulation results revealed that direct solar radiation has significant impact on heating and cooling load. If the current level of thermal mass, and thermal insulation were maintained, and the nighttime ventilation was not utilized, controlling the direct solar radiation in the house would reduce the heating and cooling load of the house by 31% .

If window shading does not exist, the house will maintain a comfortable air temperature for only 35%, 32% and 41% of the year in the south, east and north zones respectively (Table 4-6). (Figure 4-20).

Table 4- 6: House performance without window shade.

	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26 C	46.00	163.00	169.00	120.00
Number of Under Heating Hours with temperature<18C	162.00	24.00	24.00	48.00
Total Number of Hours simulated	288.00	288.00	288.00	288.00
percent of over Heating hours %	15.97	56.60	58.68	41.67
percent of under Heating hours %	56.25	8.33	8.33	16.67
percent of cofortable air temperature hours %	27.78	35.07	32.99	41.67

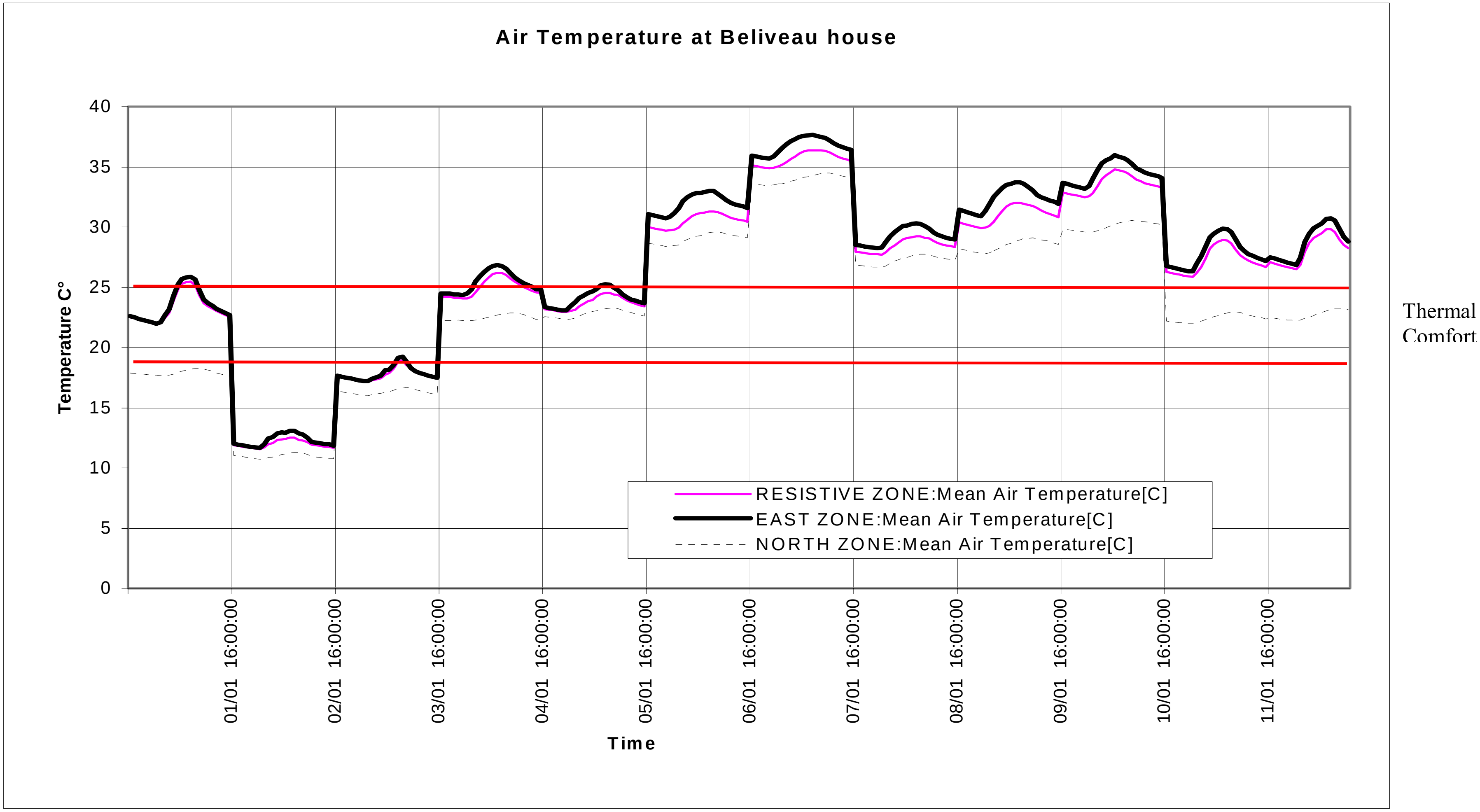


Figure 4- 20 : House performance without window shade.

4-7-3-4: Natural Ventilation;

When coupled with thermal mass, solar radiation, and thermal insulation, natural ventilation had significant impact on the house's cooling load.

Under the current house construction, and nighttime ventilation from 8pm-6am during August to September. $2m^2/s$ of natural air ventilation was introduced through mechanical ventilation, the house maintained comfortable air temperature for 88%, 87% and 81% of the year in the south, east and north zones respectively (Table 4-7)(Figure 4-21). A range of natural ventilation rates were tested to determine the appropriate ventilation rates, the house performance under different ventilation rates is shown in appendix 1.

Table 4- 7: House performance with nighttime ventilation rate of $2m^2/S$.

	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26 C	46.00	12.00	14.00	6.00
Number of Under Heating Hours with temperature<18 C	162.00	24.00	24.00	48.00
Total Number of Hours simulated	288.00	288.00	288.00	288.00
percent of over Heating hours %	15.97	4.17	4.86	2.08
percent of under Heating hours %	56.25	8.33	8.33	16.67
percent of cofortable air temperature hours %	27.78	87.50	86.81	81.25

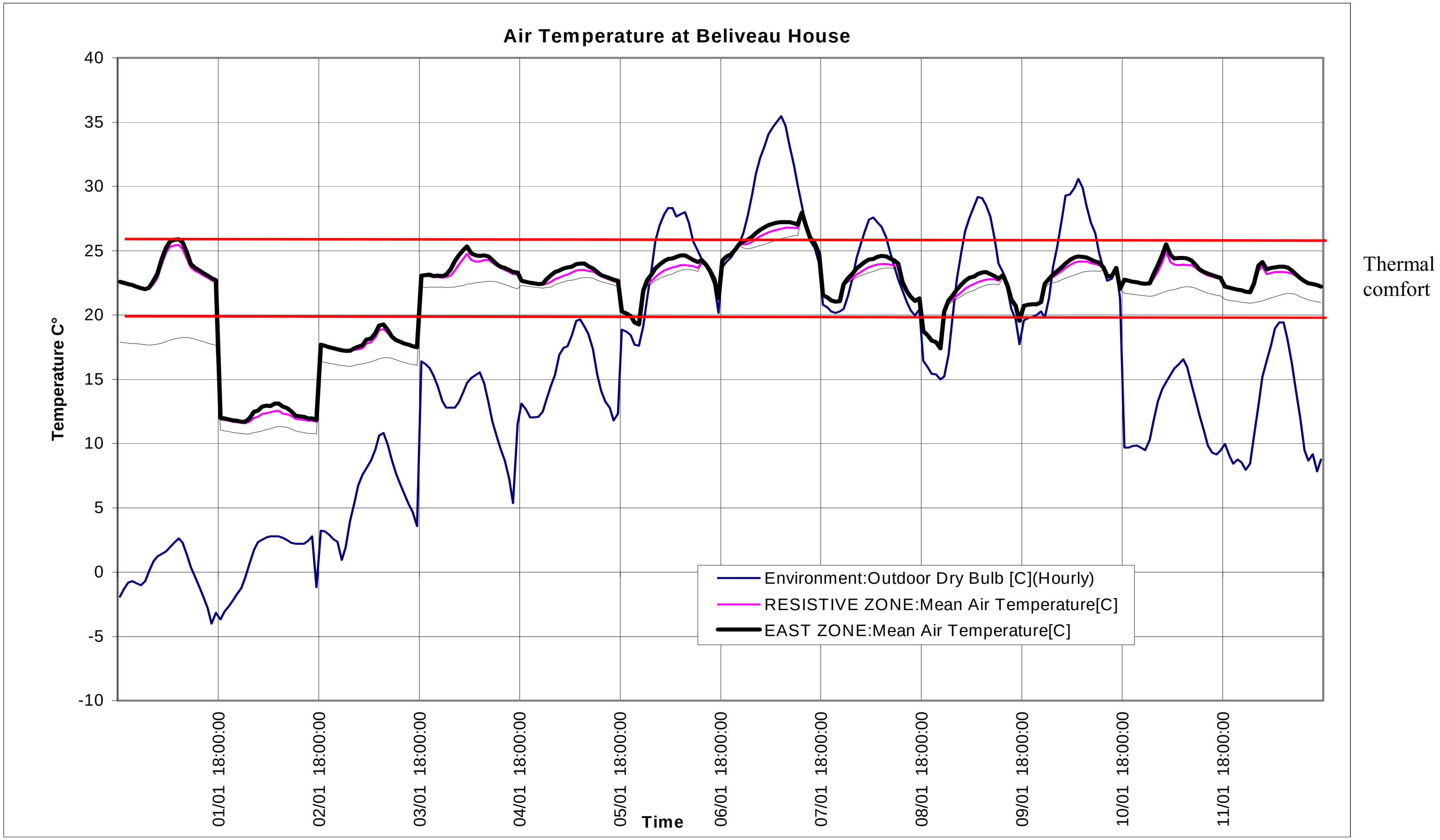


Figure 4- 21 : Beliveau house performance with nighttime ventilation.

4-7-3-5: Statistical analysis;

The statistical analysis engine loaded the simulation input and output files in Microsoft Excel© sheets, Using the statistical functions in the Microsoft Excel© software, statistical analysis was conducted examine the effect of the solar radiation, thermal mass, thermal insulation, natural ventilation, and the heating/cooling load of the house. The statistical analysis results were as follows:

A regression analysis was performed for the Beliveau House to estimate the effect of four independent variables: 1) heat transmittance through the insulation (U), 2) the transmittance of the south-facing glass (ST), 3) the south zone concrete slab thickness in the first floor (TH), and 4) the ventilation air flow rate (VENT) on one dependant variable, cooling energy. The relationship may be estimated by the following expression:

Cooling Energy = -6.7 + 6.22 U +21.7 ST - 0.01 TH – 0.4 VENT.

Where;

Cooling Energy = the cooling energy (kw/h) which is needed to maintain the house within the comfort zone, and within a controlled air temperature of 18-26C.

U = transmittance of insulation ($w/m^2.C^o$)

ST = fraction of glass solar radiation transmittance.

TH = concrete slab thickness which faces the south window (mm).

VENT = air ventilation rate transformation function which is (X^2 - X) where X is the air ventilation rate (m^3/second).

The regression analysis result is presented in table 4-8.

Table 4- 8; Regression analysis between cooling energy, insulation U value, glass transmittance, floor slab thickness, and air ventilation rate.

Regression Statistics	
Multiple R	0.973763761
R Square	0.948215862
Adjusted R Squ	0.933420394
Standard Error	0.950468812
Observations	19

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	231.5870332	57.8967583	64.08826378	7.62657E-09
Residual	14	12.64747347	0.903390962		
Total	18	244.2345067			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-6.71643213	1.386843548	-4.8429631	0.000260676	-9.690918357	-3.741945904
ST	21.73913584	2.977870635	7.30022842	3.9082E-06	15.35223286	28.12603882
TH	-0.019867073	0.005559612	-3.573463724	0.003055224	-0.031791266	-0.00794288
U	6.226219214	0.587763866	10.59306224	4.55507E-08	4.965589977	7.48684845
VENT	-0.400857525	0.172720267	-2.320848221	0.035901014	-0.771305985	-0.030409066

A regression analysis was also carried out between the average hourly solar radiation gain (SOL), heat transfer in building envelope (HT), and the building thermal mass (MASS) and thermal load is presented in the following relation;

Cooling Energy = -3.9 +1.22 HT+ .93 SOL-1.05 MASS

where;

SOL= The total direct and indirect solar radiation (kW/h) admitted through the building envelop.

H T= heat gain or loss through the building envelope (kW/h).

MASS= the overall internal mass of the building which is placed in the floor slab (ton/m^2 of concrete floor structure).

The regression analysis result is presented in table 4-9.

The correlation coefficient between the hourly average solar radiation, the average heating gain/loss through the building envelop, and the thermal mass against the heating/cooling load of the building was 99.5, 99.2, 98 respectively. The relation between solar radiation and the heating load is presented in (Figure 4-22).

Figure 4-23 shows the relationship between envelope heat transfer and average heating energy. Figure 4-24 shows the effect of thermal mass, thermal insulation solar radiation on heating and cooling load, and figure 4-25 shows the thermal comfort levels which achieved by integrating thermal mass, thermal insulation, solar radiation, and natural ventilation.

Table 4- 9; Regression analysis between thermal load and thermal mass, thermal insulation and solar radiation.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.996867431
R Square	0.993744674
Adjusted R Squa	0.992301138
Standard Error	0.340753439
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	239.7997557	79.93325192	688.4097	1.43614E-14
Residual	13	1.509467782	0.116112906		
Total	16	241.3092235			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-3.917309079	0.185095511	-21.1637173	1.86E-11	-4.317183543	-3.51743
load	1.228589075	0.058956523	20.83889973	2.26E-11	1.101221275	1.355957
sol	0.936086309	0.024708985	37.88445026	1.08E-14	0.882705803	0.989467
mass	1.052072115	0.069909772	15.04899926	1.33E-09	0.901041263	1.203103

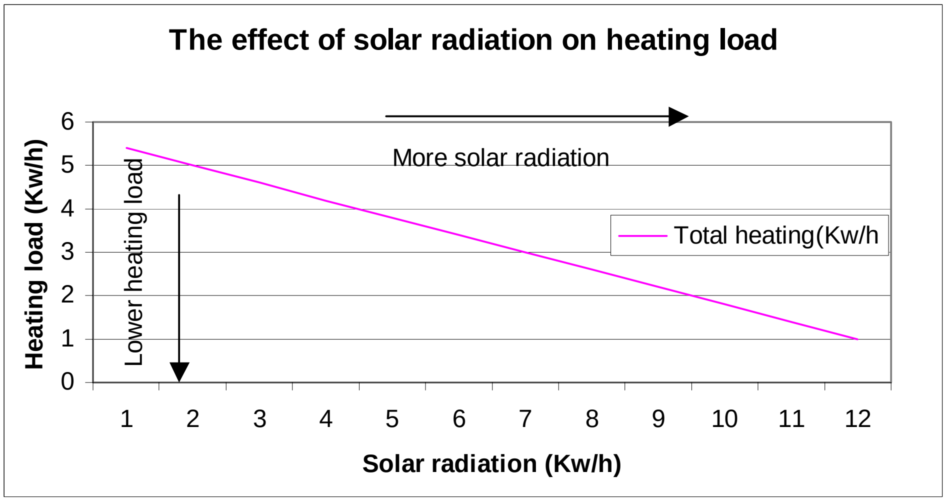


Figure 4- 22: The relation between the solar radiation gain and the heating load at Beliveau house.

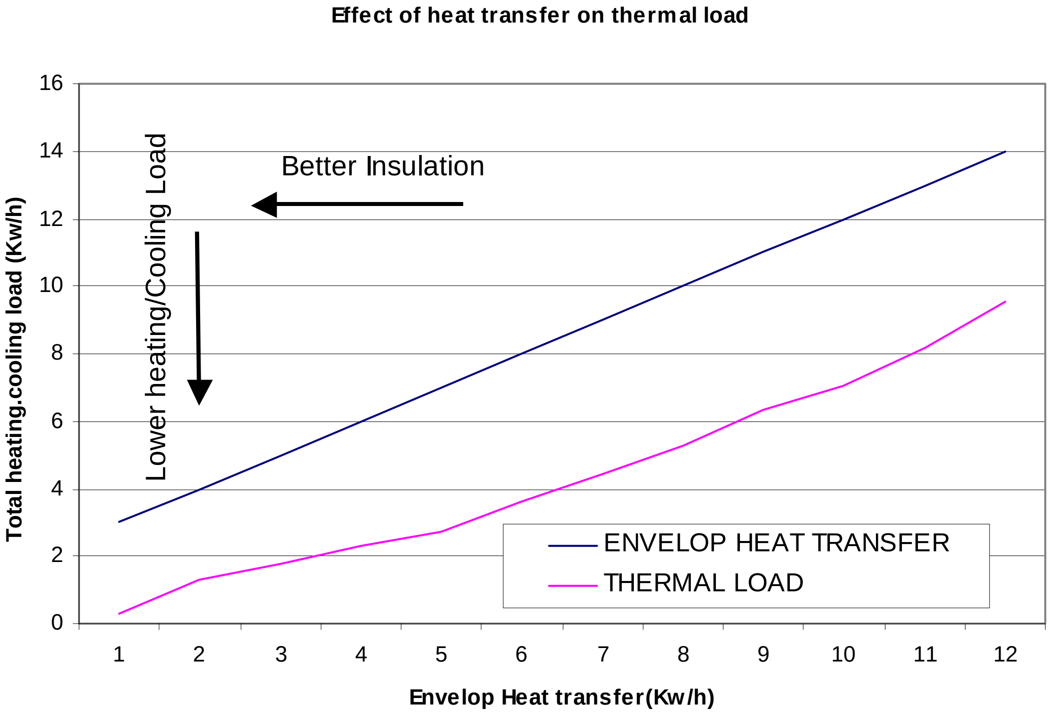


Figure 4- 23: The relation between the thermal insulation and the heating load.

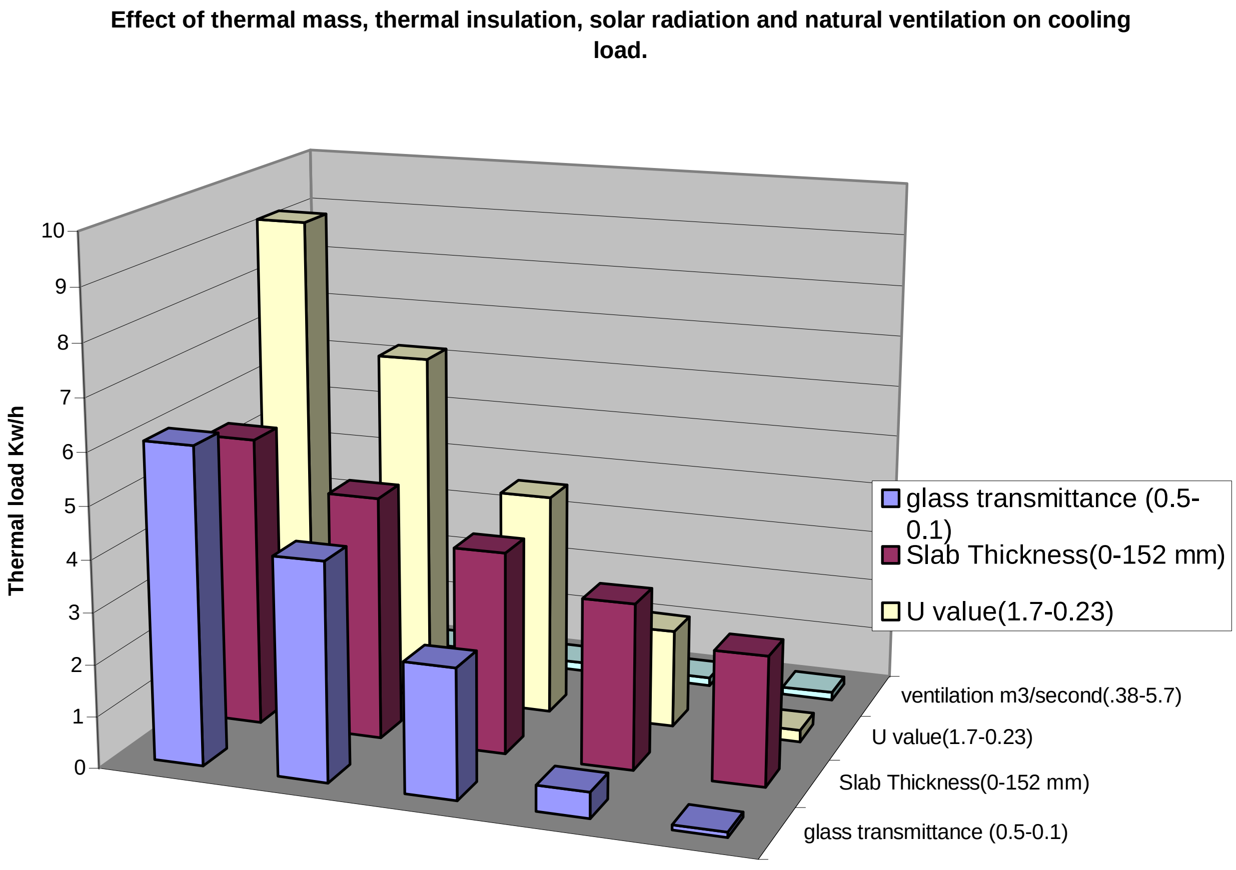


Figure 4-24: Effect of thermal mass, thermal insulation, solar radiation, and natural ventilation on cooling load.

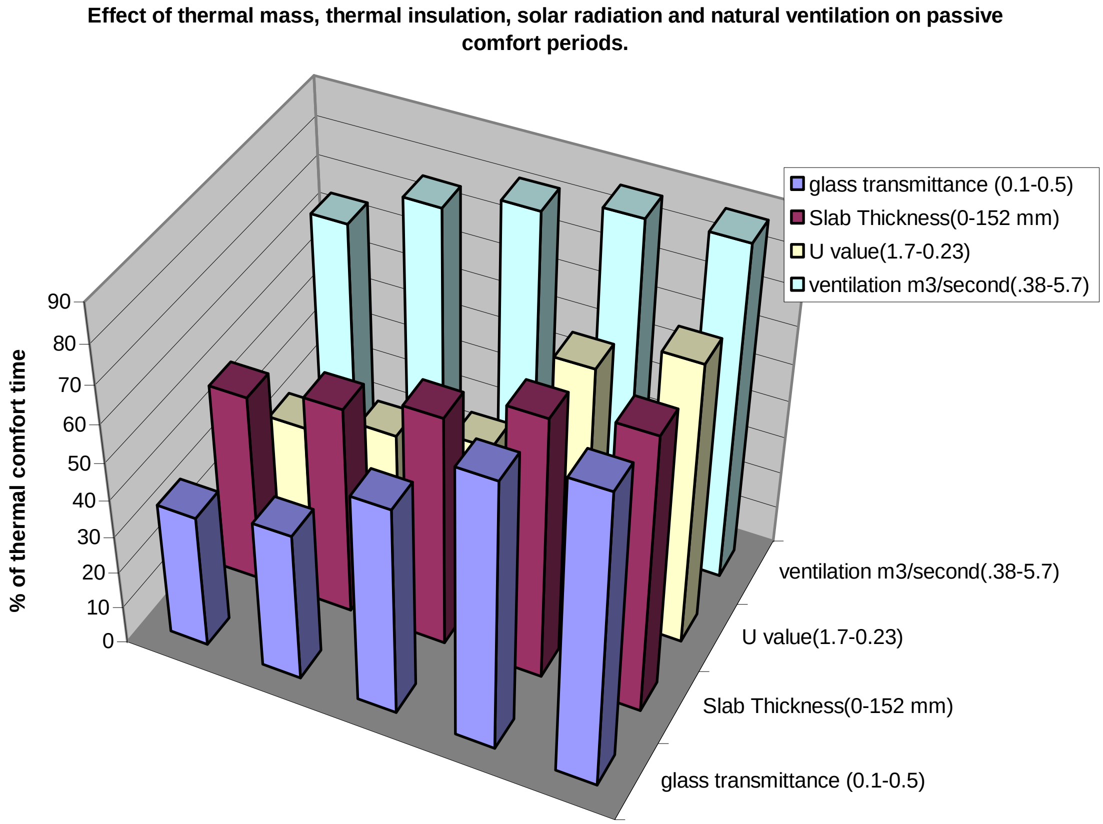


Figure 4- 25: Effect of thermal mass, thermal insulation, solar radiation, and natural ventilation on achieving passive thermal comfort.

4-8 Discussions of building performance;

In conclusion, Beliveau house energy performance can be summarized as follows:

1- Thermal insulation had the highest effect on the heating and cooling load, within the practical range of thermal insulation that has been established in evaluating Beliveau house, increasing thermal insulation was shown to have positive effect on reducing both heating and cooling load.

2- Controlled solar radiation has the second major effect on heating and cooling load. Controlling solar radiation can be achieved by using fixed shading devises such as roof overhang or fixed vertical shading devices and movable shading devices.

3- Thermal mass has the third major effect on heating and cooling load. Thermal mass plays a major role in balancing the heating and cooling load in moderate days. Although energy saving which is accomplished as a result of the thermal mass was not great. Thermal mass has significant impact on increasing the hours where comfort air temperature was achieved under passive mode.

   Sensible thermal mass is widely used to store sensible heat. However, latent heat storage of building materials is very important as well. Although increasing the building sensible thermal mass is difficult to achieve especially in conventional wood construction, building latent heat storage is usually high in most buildings, and can be utilized to reduce the latent cooling load.

4- The effect of thermal insulation, thermal mass and solar radiation must be integrated and are interactive. The building evaluation of Beliveau house showed that a balance should be achieved between the amount of thermal insulation, which is used, the amount and duration of controlled solar radiation admitted through building fenestration, and the quantities and distribution of thermal mass in buildings.

5- The simulation results also showed that a significant part of the cooling load is in a form of latent heat, which is due to ventilation and internal moisture gain . Thermal mass is referred to the sensible heat storage only. However, building materials also have big potentials for storing latent heat by water absorption and desorption.

6- Since the house thermal balance point was lower than the outside air temperature in most overheating periods. Nighttime ventilation and natural ventilation have good energy saving potentials. However, careful attentions should be made to control high relative humidity.

7- The analysis also showed that in the absence of solar radiation, there is a negligible relation between the building mass and the heating /cooling load. On another hand, in the absence of the direct solar radiation, the thermal mass showed different impact on energy saving in the cooling periods compared to the heating periods. The thermal mass has positive impact on energy savings in both the cooling periods and the days where there is a big variation in the climate condition in a short period of time, the correlation coefficient between indirect solar gain and the thermal mass in these periods was .98. At the same time the analysis showed negative impact of thermal mass on energy saving in the long heating periods with nighttime temperature setback, the correlation coefficient between indirect solar gain and the thermal mass in theses periods was .99. It should also be pointed out that the direct solar radiation gain is the radiation admitted to the space in its short wave (mainly through the windows). While the indirect solar radiation gain is the impact of the solar radiation that hits the outside building surfaces and generates energy impact on the building.

4-9 Improving the house performance;

Based on the house evaluation results, the thermal mass, thermal insulation, solar radiation, and the ventilation rates were modified at the Beliveau house to improve its thermal performance. The insulation was increased to 100mm(U= .23W/m^2), the thermal mass in the floor was also increased to 120mm, the window screens were shut down during summer, and a nighttime ventilation of 2m^3/second was introduced from 9PM to 6AM in the morning.

The house performance was improved significantly, the house maintained the inside air temperature within a range of 18C°-26C° for approximately 84% of the year in the south zone of the house and 82% in the east zone of the house. The underheated period was 8.3% for the south and the east zone and 16.6% for the north zone. The overheated period was 4.2% in the south zone, 4.9% in the east zone and 2.1% in the north zone.(Figure 4-26) (Table 4-10).

However these strategies did not solve the humidity problems. The relative humidity under these strategies stayed over 75% for 40% of the cooling season, which means the thermal comfort was not fully achieved (Figure 4-27). To solve this problem, new ventilation strategies were suggested in the following chapter.

Table 4- 10 ;Revised Beliveau house thermal performance.

	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26 C	46.00	12.00	14.00	6.00
Number of Under Heating Hours with temperature<18 C	162.00	24.00	24.00	48.00
Total Number of Hours simulated	288.00	288.00	288.00	288.00
percent of over heating hours %	15.97	4.17	4.86	2.08
percent of under heating hours %	56.25	8.33	8.33	16.67
percent of comfortable air temperature hours %	27.78	87.50	86.81	81.25

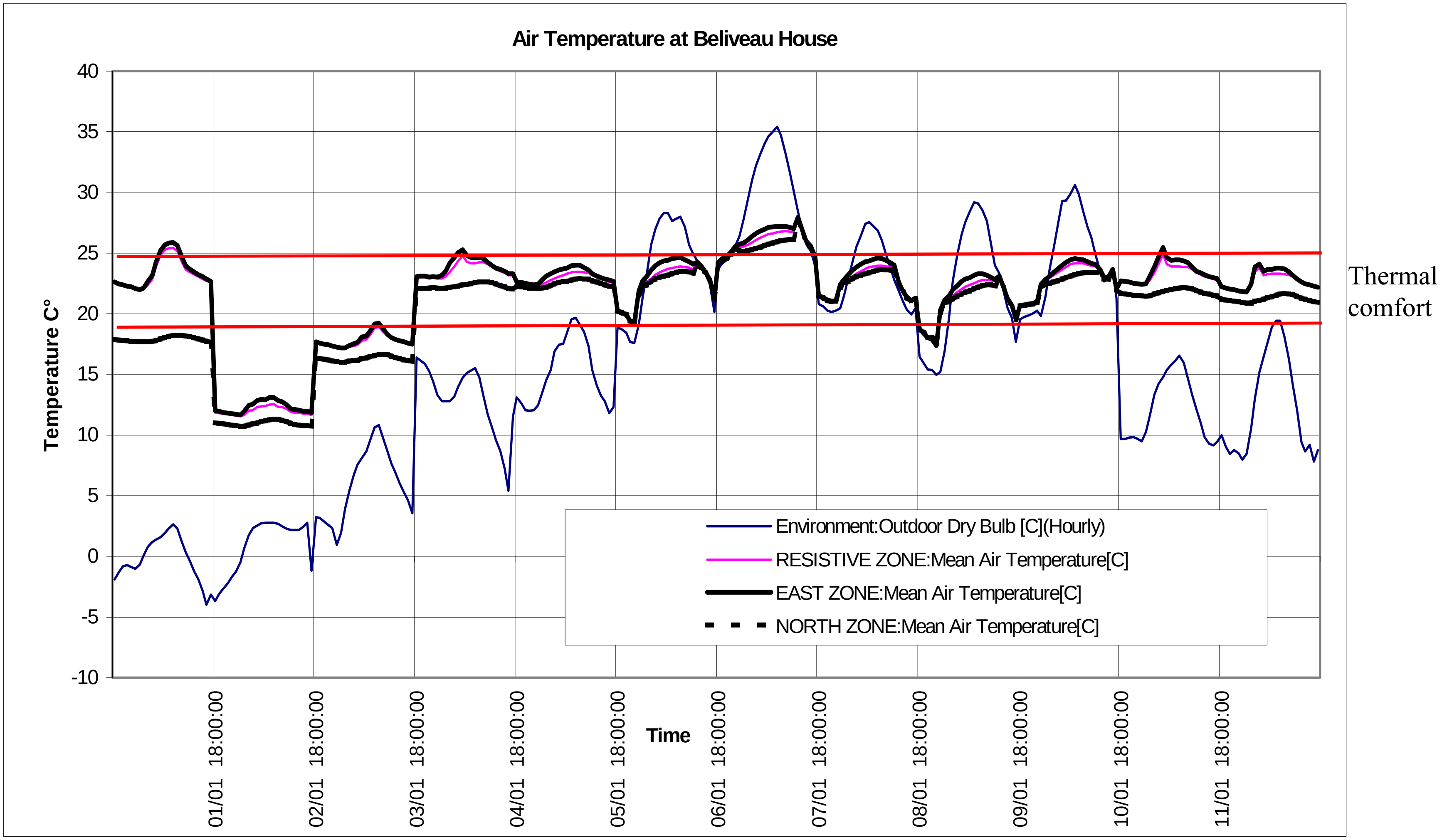


Figure 4- 26: Beliveau house performance after revising the thermal mass, thermal insulation, solar radiation, and natural ventilation.

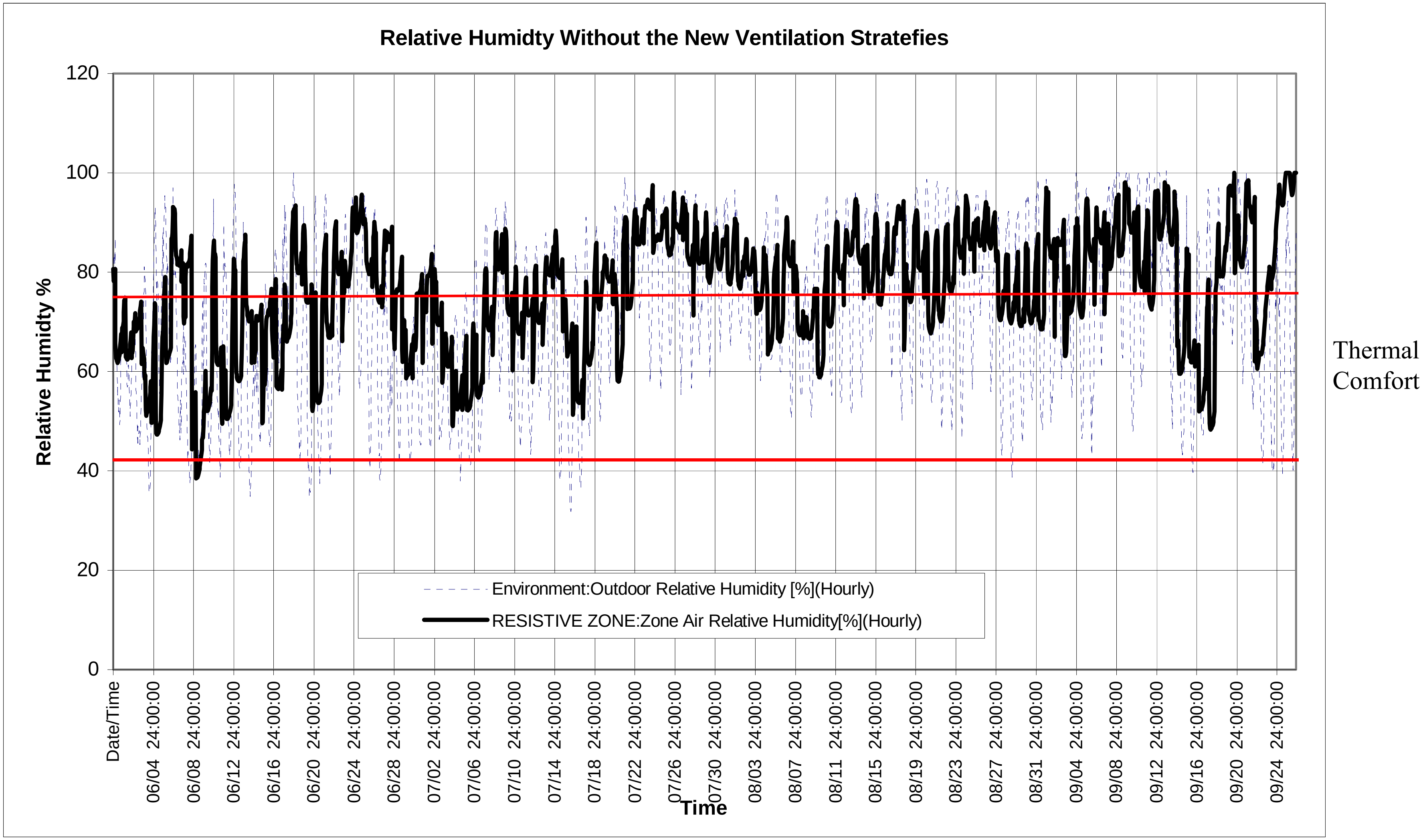
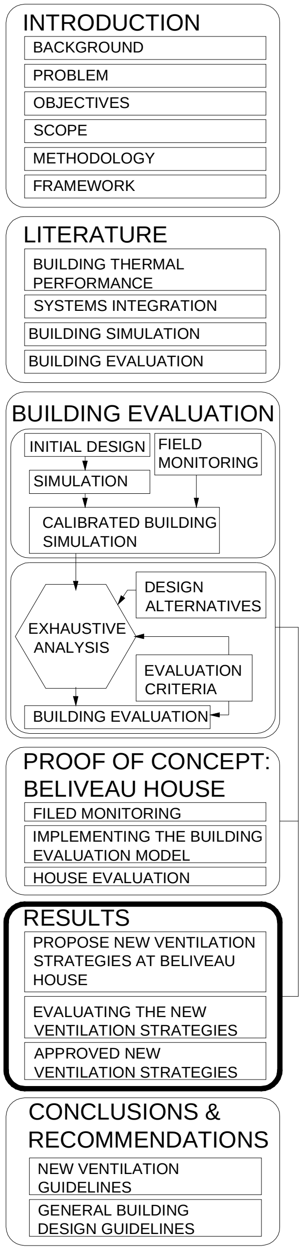


Figure 4- 27: Relative humidity at the Beliveau house during the cooling period.

Chapter Five

V:New Energy Conservation Strategies

V:New Energy Conservation Strategies..........................117



V New energy conservation strategies;

5-1 Over view;

In the previous chapter, the evaluation model was used to reveal the actual performance and the real contribution of the major building elements to energy saving at Beliveau house. It was clear that controlling solar radiation, increasing thermal mass, and optimizing thermal insulation are the targets for future measures to enhance Beliveau house energy performance. However, modifying the Beliveau house thermal insulation or thermal mass is not practical, and improving or automating the shading devices to control solar radiation is also not technically or economically feasible in this particular case. Further more, relative humidity was not addressed in improving the house performance except in under sizing the heat pump which is equivalent to utilizing the newly available variable speed heat pumps as was discussed earlier in section 2-1-6 in the literature review.

In light of these facts, the proposed energy conservation strategies are based on supplemental measures, which have similar effects to controlling thermal mass, thermal insulation, and solar radiation.

As a supplement for controlling the thermal insulation and solar radiation, this research suggests indirect natural ventilation, which controls the amount of heat gain admitted to the space, and as a supplement to the controlled sensible thermal storage, This research suggested controlled latent heat storage by introducing direct ventilation through the heat exchanger.

These new strategies are based on integrating direct and indirect natural ventilation through a heat exchanger coupled with the HVAC system to reduce the cooling load, reduce relative humidity, improve the indoor air quality and enhance thermal quality.

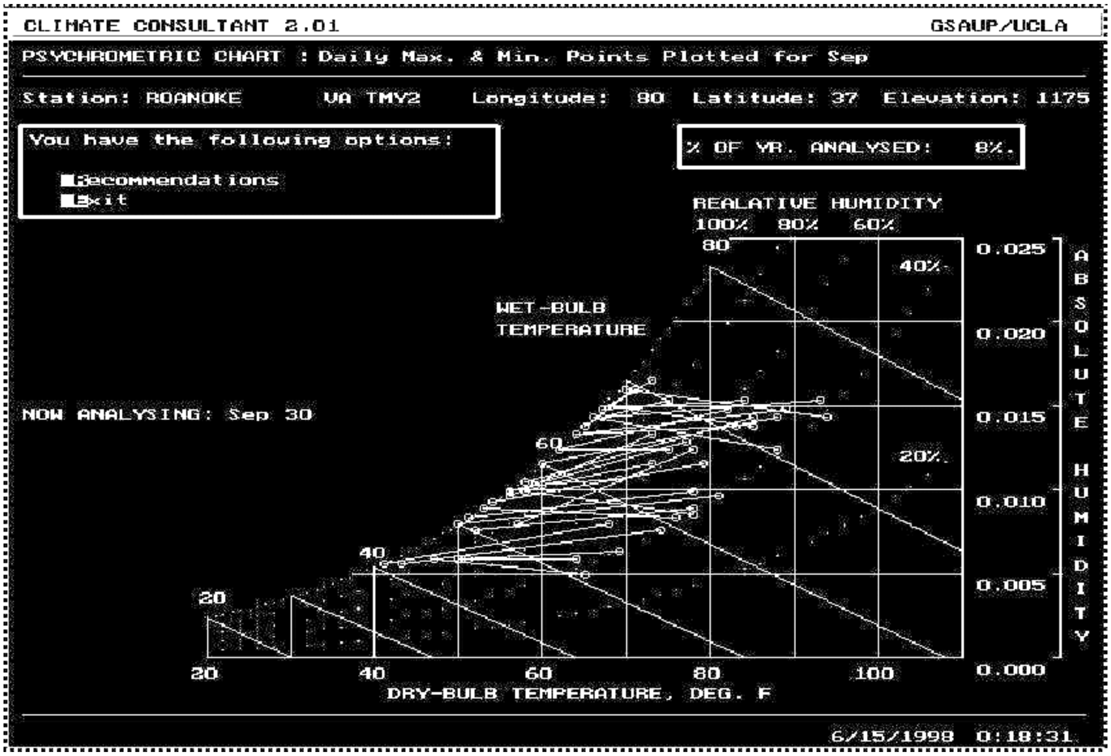
5-2 Background:

Traditionally, utilizing nighttime ventilation and thermal mass is one of the major passive cooling strategy in dry climates. However, passive cooling through ventilation is more difficult to achieve in moderate and humid climates. In these climates, the outside air cools down during the early night hours, but its relative humidity stays high. Therefore, the outside air is not suitable for nighttime ventilation.

Later at night, outside relative humidity reaches the comfort level, but the outside air enthalpy remains equal or more than the inside air enthalpy. Thus, starting nighttime ventilation may reduce the inside air temperature, but without reducing the air enthalpy. Instead it may lead to more moisture absorption of inside building materials and furniture (Isetti,1988). During daytime, more moisture is produced inside the building due to the required ventilation and other inside humidity sources. In most cases, dehumidification is needed to extract the excess moisture. Thus, more active cooling is needed to extract the extra moisture, which is admitted to the space during nighttime ventilation.

Figure 5-1 presents the Climate Consultant 2.01© software output of the daily minimum and maximum air temperature in August for a moderate and relatively humid climate (Roanoke area). As the chart shows, during moderate summer days, the outside air continues to cool down and starts to lose some of its moisture and enthalpy. Traditionally, nighttime ventilation starts when outside air temperature is lower than the inside air temperature, and the outside relative humidity is acceptable. Selecting early night hours for nighttime ventilation was seen useful to maximize the benefit of the thermal mass. In most cases, during late night and early morning hours, cold air cannot be introduced into the building by direct ventilation in order to maintain the inside air temperature within the comfort level. Thus the direct nighttime ventilation does not fully use the low enthalpy air at these times (Figure 5-2).

Conventional building materials usually store heat efficiently for short periods of time. However, moisture content of building materials and furniture varies widely in their capabilities to store moisture. In addition, to achieve


CLIMATE CONSULTANT 2.01 GSAUP/UCLA

PSYCHROMETRIC CHART : Daily Max. & Min. Points Plotted for Sep

Station: ROANOKE VA TMY2 Longitude: 80 Latitude: 37 Elevation: 1175

You have the following options:

% OF YR. ANALYSED: 8%.

NOW ANALYSING: Sep 30

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Figure 5- 1: The air moisture content of the air on September. The chart was obtained from Climate Consultant simulation to Roanoke area (Climate Consultant, 2002).

comfort, usually the air temperature tolerance in a space should not exceed 5-6 C° (the limits of the comfort zone), but the comfort level can be achieved with a wide relative humidity range of approximately 30-60%. Thus, the latent heat released from the building materials can significantly contribute to cooling loads. In addition, the inside relative humidity is lower during the day when nighttime indirect ventilation was operating. If active cooling is still required during the day, thermal comfort can be achieved at higher air temperatures because the inside relative humidity is relatively low, and at the same time, less dehumidification is required.

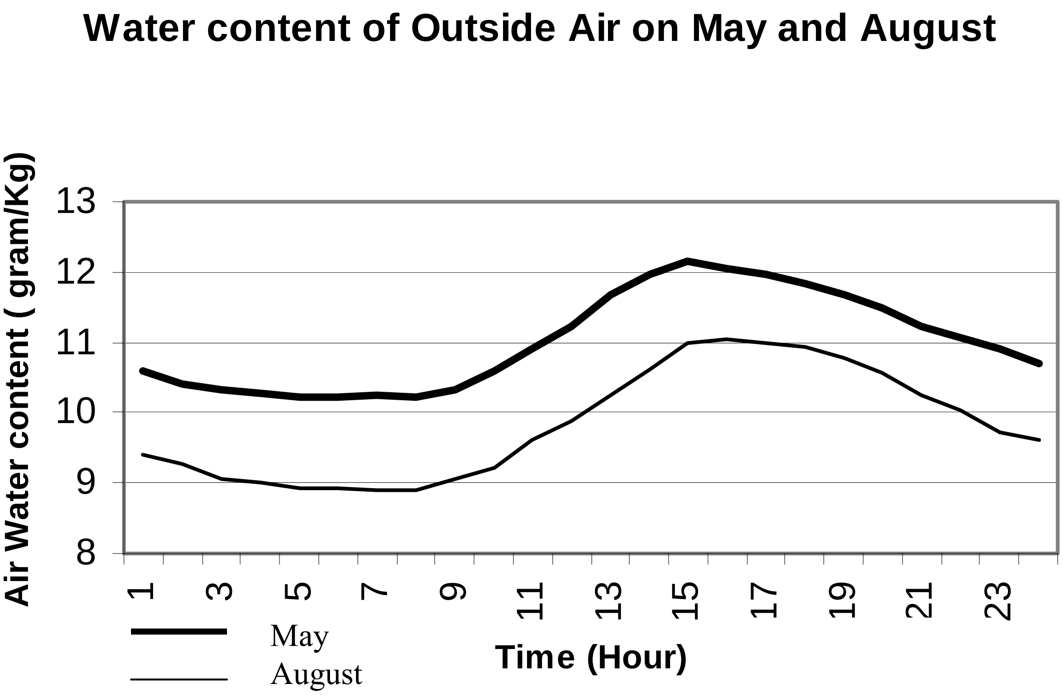


Figure 5- 2: Water content of outside air in Blacksburg area. The initial data obtained from Roanoke TMY weather data file.

5-3 Direct/Indirect Nighttime Ventilation strategies;

To overcome the shortcoming of direct nighttime ventilation, this research integrates direct and indirect ventilation through sensible air-to-air heat exchanger. In this approach, two air ventilation loops are used. The first is indirect ventilation, and the second is air ventilation through the sensible heat exchanger. The following are the running scenarios of these natural ventilation strategies:

5-3-1 Indirect ventilation;

This strategy is used when outside air temperature is lower than inside air temperature, and outside enthalpy is higher or equal to the inside enthalpy. In this case, outside air will pass through the exterior chamber of the sensible heat exchanger and the inside air will pass thorough the interior chamber of the heat exchanger (Figure 5-3). Thus, the building will use the outside cool air without gaining moisture. The air circulation rate should be optimized to maintain the indoor air temperature within the comfort level, and the active cooling system will supplement the extra cooling load if required.

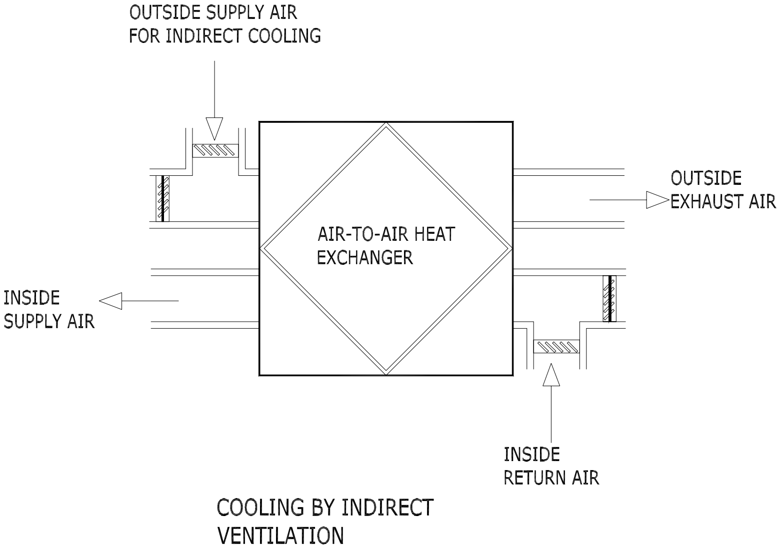


Figure 5- 3: Cooling by indirect ventilation.

5-3-2 Direct air ventilation;

When the outside air temperature is lower than inside air temperature and outside enthalpy is also lower than the inside enthalpy: outside air will be exchanged with the inside air through the sensible heat exchanger (Figure5-4). The low enthalpy outside air replaces the higher enthalpy inside air while maintaining the inside comfortable air temperature. During this time, the inside building materials and furniture will release some of its moisture. Bypass direct air ventilation will also allow for direct ventilation. The air circulation rate in both heat exchanger chambers is optimized to maintain comfort.

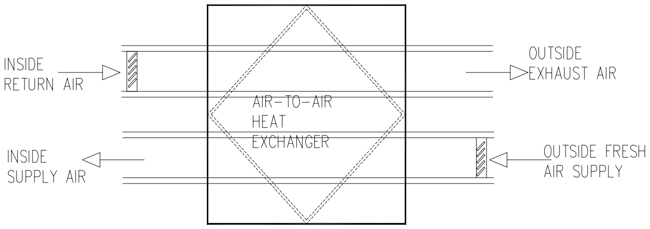


Figure 5- 4: Cooling and dehumidification through heat recovery and indirect ventilation.

5-3-3 Integrating direct and indirect ventilation;

This research presents a holistic approach of integrating direct and indirect ventilation to reduce sensible cooling load, and direct ventilation through the heat exchanger to reduce latent cooling loads. The overall ventilation operation and control framework is presented in Figure 5-5. The mechanical system, which is required to integrate direct ventilation through heat exchanger, direct ventilation, and indirect ventilation is presented in Figure 5-6. It consists of an air-to-air heat exchanger, heat pump, variable volume fan coils, air controllers, air distribution system, and weather condition controller. Since this research proposes new direct nighttime ventilation through heat exchanger and indirect ventilation. EnergyPlus is not designed to simulate these ventilation strategies. Therefore, two heat exchangers where used in the simulation instead of one which is needed. The fan motor of one of the heat exchangers was sit outside the air loop to neutralize its effect on internal heat gain.

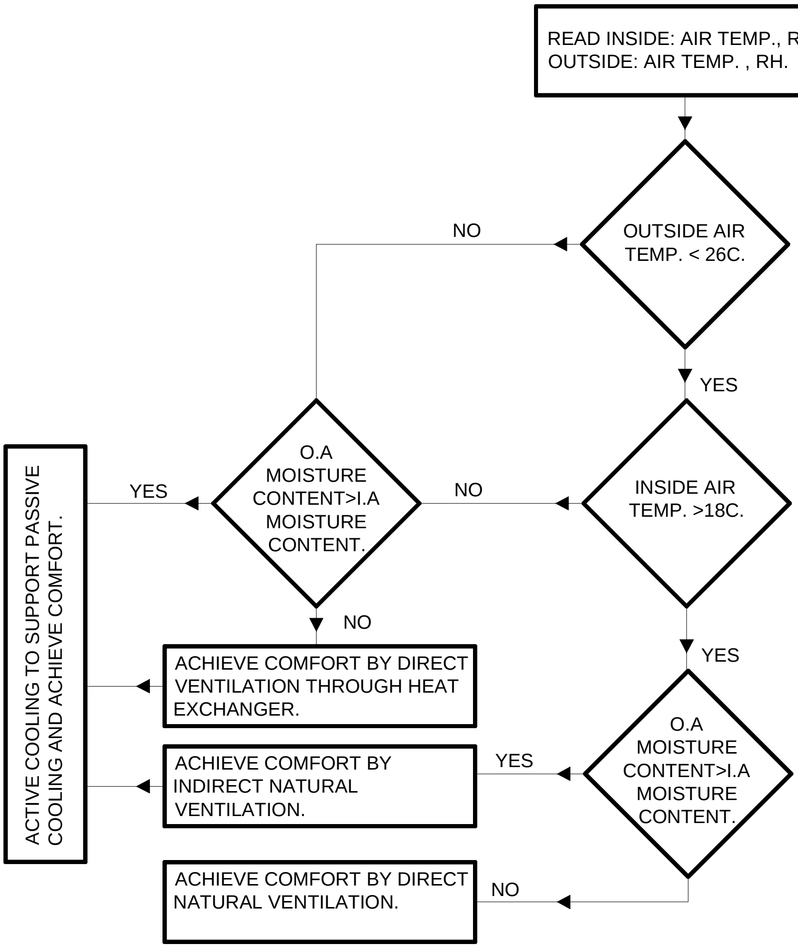


Figure 5- 5; Schematic diagram of integrating the new ventilation strategies in the HVAC control system .

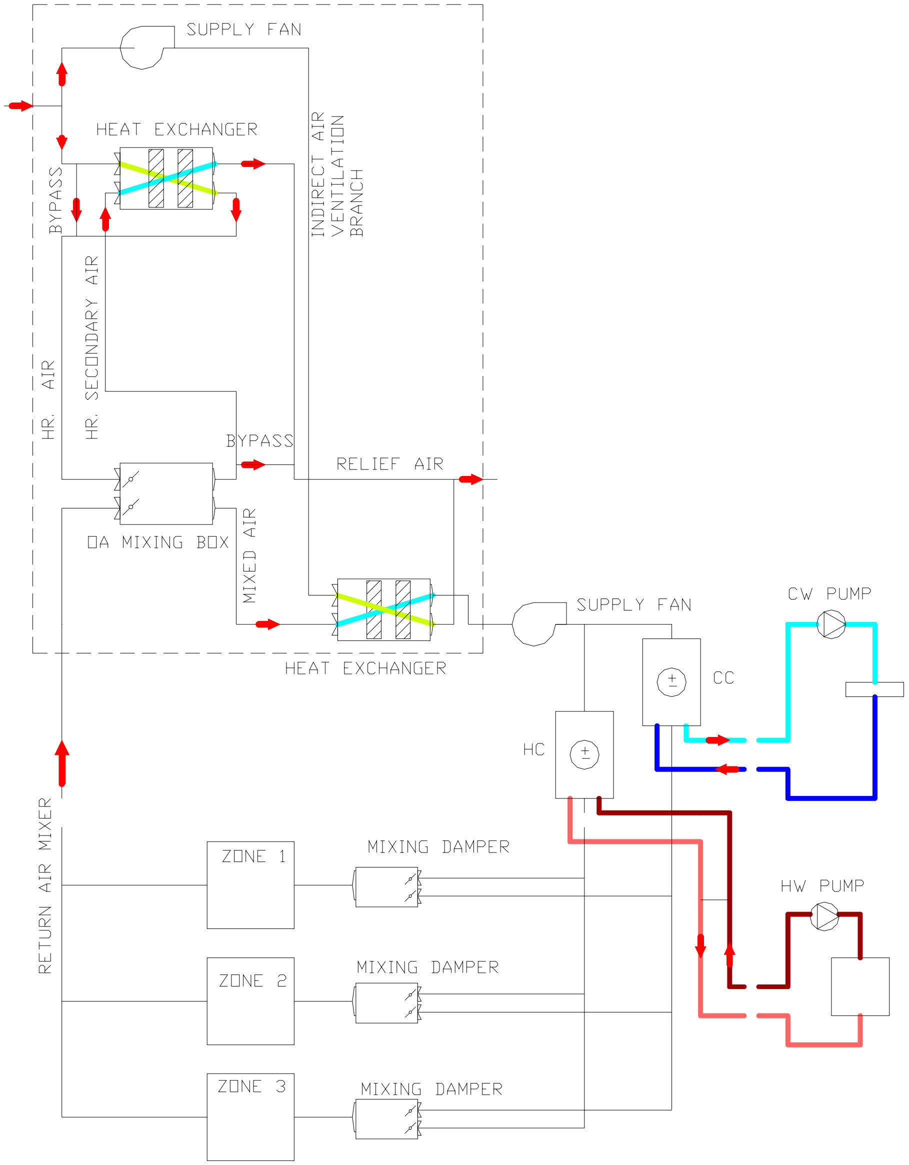


Figure 5- 6: Schematic diagram of integrating heat exchanger in the mechanical system to incorporate the new ventilation strategies.(The two heat exchangers, cold-water loop, and hot-water loop in this chart are presented only for simulation purposes. The actual system will have one heat exchanger, and a cold/hot water loop).

5-4 Testing;

To test the proposed ventilation strategies potential energy saving, the evaluation model was used to derive relations between thermal loads as the dependent variable, and direct and indirect natural ventilation rates as the independent variables.

The solution generator in the evaluation model was used to generate different building alternatives with five different outside air ventilation rates of 1, 3, 6, 9, 12,15 m^2/s air changes per hour. Since the goal of this test is to reveal the effect of the sensible and latent thermal storage on energy saving, the sensible and latent heat load was analysed separately. The simulation was done in the following stages:

5-4-1Cooling by direct ventilation;

When the outside air enthalpy is lower than inside air enthalpy, and the outside air temperature less than the inside air temperature, direct natural ventilation is used for cooling. The mechanical ventilation was used to derive outside air. To compensate for air friction and mechanical system heat gain, 1/2C° was added to the temperature of the mechanically driven outside air (Jones, 1996).

5-4-2 Cooling by direct ventilation through heat exchanger;

When outside air has less moisture content than inside air, and the inside air temperature is in the lower limits of the comfort zone but higher than outside air temperature, direct natural ventilation if used will lower inside air temperature below the acceptable levels for comfort. Instead, direct natural ventilation through the heat exchanger is used to dry up the building interior without breaching the thermal comfort requirements.

EnergyPlus© has outside air controller which monitor the inside thermal comfort condition and switch between direct natural ventilation and ventilation through the heat exchanger to maximize the ventilation rate without breeching the assigned comfort level. The air-to-air heat exchange efficiency was assumed 87%.

5-4-3 Cooling by Indirect air ventilation;

When the moisture content of the outside air is more that the inside air moisture content, and the outside air is cooler than the inside air, indirect air ventilation is used to cool the building. Since a sensible heat exchanger is used in the indirect air ventilation, the sensible thermal cooling load only was considered in predicting the effect of the indirect natural ventilation on the cooling load. The air-to-air heat exchange efficiency was assumed 87%, and 1/2C° were added to the temperature of the mechanically driven inside air to compensate for air friction and mechanical system heat gain.

5-4-4 Moisture simulation;

The latent cooling load saving cannot be achieved unless there is sufficient latent heat storage in the building. The latent thermal storage is the sorption and desorption capacity of the interior building materials. To check the sorption and desorption capacity of the Beliveau house, the MOIST software was used to simulate the moisture sorption and desorption capacity of the house major building materials.

The MOIST software dynamically simulates the moisture content of the building materials under different climate conditions. The same weather condition, which is used in EnergyPlus©, was used in the MOIST software. The MOIST software simulates the moisture and the heat transfer in the building envelope.

The moisture sorption and desorption of building materials occur over long time periods. MOIST manual suggests that the building material requires six months to reach the moisture balance from the initial simulation time (Burch, 1997). Furthermore, most building materials have two moisture sorption and desorption cycles, a daily and a seasonally cycle. For example, gypsum board and carpet have high daily fluctuation and low seasonally moisture content fluctuation, while concrete and wood have low daily fluctuation and high seasonal moisture content fluctuation.

The MOIST was used to simulate the Beliveau house exterior walls. The MOIST software is designed to test only the moisture behaviour of buildings envelopes. Therefore, in order to simulate the moisture behaviour of the internal walls and furniture by the MOIST software, the internal walls was simulated as if they are external walls. Virtual “Non-storage” materials were added to the internal walls to keeps their surface temperature equal to the internal air temperature without affecting its moisture absorption behaviour. The simulation results were based on the assumption of an internal moisture generating rate of 12 to 24 lb/day (Szokolay, 1980), maximum inside air temperature of 26C°, and maximum inside relative humidity of 56% were also assumed.

The average and minimum daily water sorption of the building materials at the Beliveau house is exhibited in Figure 5-7. This figure shows that the mean minimum daily moisture sorption and desorption of the house building materials are more than the maximum moisture desorption that can be achieved from the direct ventilation, Therefore, accounting for seasonal variation in building moisture content is not necessary at this particular house.

It should also be noted that other building materials such as furniture, books, and clothing have significant amount of moisture sorption capabilities which increse the latent thermal storage of the buildings.

The simulation result of the MOIST software also showed that moisture desorption and absorption rate of the Beliveau house building materials varies. While carpet, gypsum board, thermal insulation, and cloth furniture absorb and desorbs moisture and approach the moisture balance point in short period of time (less than 12 hours), concrete slab can take more than one month to approach the moisture balance point. These variations in moisture absorption and desorption balance the dehumidification required for the house over a longer period.

The above simulation results showed that the house has higher latent heat storage capacity than what the proposed strategies for dehumidification by ventilation may require. Thus the determining factor of the latent heat storage capacity of the house is the effective air ventilation rates.

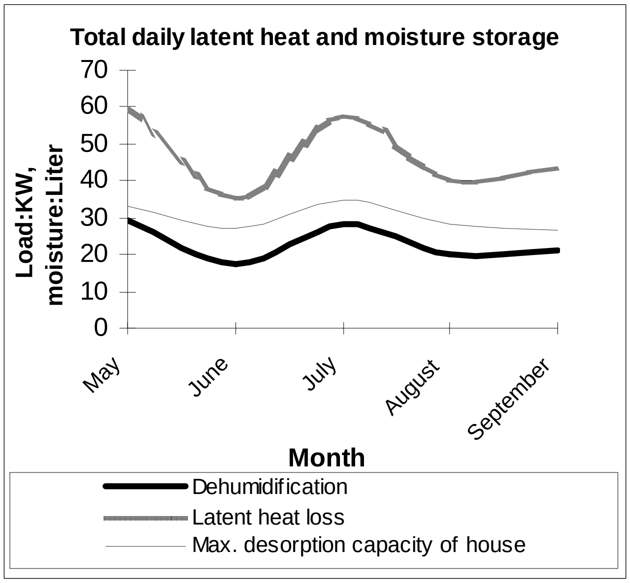


Figure 5- 7: Total internal moisture storage fluctuation (liter), maximum dehumidification(liter), and maximum latent heat loss(KW) which can be achieved by 10 air change/hour at Beliveau house.

5-5 Using the evaluation model to predict energy saving;

To predict the contribution of direct ventilation, indirect ventilation, and direct ventilation through heat exchanger on energy saving, a matrix of 1, 3, 6, 9, 12, and 15 air change per hour (.38-5.7 m^3/sec) ventilation rates from each of the above ventilation strategies were generated.

First, in order to test the effect of each of the above ventilation strategies on energy saving, each of the above strategies was implemented separately. Second, direct ventilation, indirect ventilation and direct ventilation through heat exchanger were integrated in a comprehensive ventilation strategy and simulated in EnergyPlus©. The new ventilation strategies were simulated in the following EnergyPlus© modules:

5-5-1 Outside air controller;

The outside air controller includes a number of user selectable limit controls. If any of the selected limits are exceeded, the outside airflow rate is set to the minimum. If all the limits are satisfied, the outside air controller does the following: if the outside air temperature is greater than or equal to the mixed return and outside air (mixed air) temperature set point, the outside air flow rate is set to the maximum; if the outside air temperature is less than the mixed air temperature set point, the outside air controller will modulate the outside air flow so that the mixed air temperature will match the mixed air set point temperature. The following outside air control limits were used to integrate the ventilation strategies;

A- Return Air Temperature Limit; This input establishes a limit control on the return air temperature. If the outside air temperature is greater than the return air temperature the outside airflow rate is set to the minimum.

B- Return Air Enthalpy Limit; This input establishes a limit control on the return air enthalpy. If the outside air enthalpy is greater than the return air enthalpy the outside airflow rate is set to the minimum.

C-Minimum and maximum outside air flow rate; This input established the minimum and the maximum outside air volumetric flow rate for the system in cubic meters per second.

D- Temperature Higher limit; this input establishes the outside air temperature high limit (C º) for economizer operation. If the outside air temperature is above this limit, the outside airflow rate will be set to the minimum.

E- Temperature lower limit; If the outside air temperature is below this limit, the outside airflow rate will be set to the minimum.

F- enthalpy limit; this input establishes the outside air enthalpy limit (in J/kg) for economizer operation. If the outside air enthalpy is above this value, the outside airflow rate will be set to the minimum.

G- Minimum Outside Air Schedule;: This schedule controls the fraction of outside airflow in the different times. It is useful for reducing the outside airflow rate to zero when needed.

5-5-2 Air-to Air heat exchanger;

The air-to-air flat plate heat exchanger is an HVAC component typically used for exhaust or relief air heat recovery. EnergyPlus allows also to bypass the heat exchanger unit when the airside economizer is operating. Through the outside air controller and the heat exchanger, EnergyPlus optimized the direct outside airflow and the direct air ventilation through heat exchanger.

5-5-3 Indirect Evaporative cooler;

EnergyPlus is not configured to simulate indirect ventilation through a heat exchanger. Therefore, The dry Coil Indirect Evaporative cooler module was used to simulate the indirect ventilation. The dry coil indirect evaporative cooler has a rigid media pad, where the adiabatic cooling takes place. The secondary air leaves the rigid media pad and enters an air-to-air heat exchanger where it cools the supply air flowing through the heat exchanger tubes. The moist secondary air is then exhausted to the environment. The secondary air stream has its own fan.

Since this research investigates the effect of indirect natural ventilation, the water flow rate in the evaporative cooler was set to zero. Thus, only the heat exchanger and the fan were used in this module. The outside air controller was used to control the secondary airflow in this evaporative cooler. The indirect evaporative cooler will run only when the outside air control limits are met.

5-6 Results;

5-6-1 Indirect and direct ventilation;

During the cooling period, the simulation results showed that under indirect air ventilation rate of .38m³/second (3 AH/Hour) the house maintained comfort air temperature for 60.5%, 71.5%, 67.6% in the north, east, and south house zones respectively (Table 5-1)(Figure 5-8). Under air ventilation rate of 5.7m³/second (15 AH/Hour) the house maintained comfort air temperature for 94.1%, 87.2%, 88.6% of the north, east, and south house zones respectively (Table 5-2)(Figure 5-10). Figure 5-9, and Table 5-3 shows the house performance under air ventilation rate of 3.6 m³/Second.

A statistical relation was made between the natural ventilation flow rates and the overheated periods (Figure 5-11). The regression analysis showed significant relation between air ventilation rate and thermal comfort (Table 5-4).

The regression equation between air ventilation rate and the overheated period is;

Over heated time= $34.17-9.96(X^2-X)$

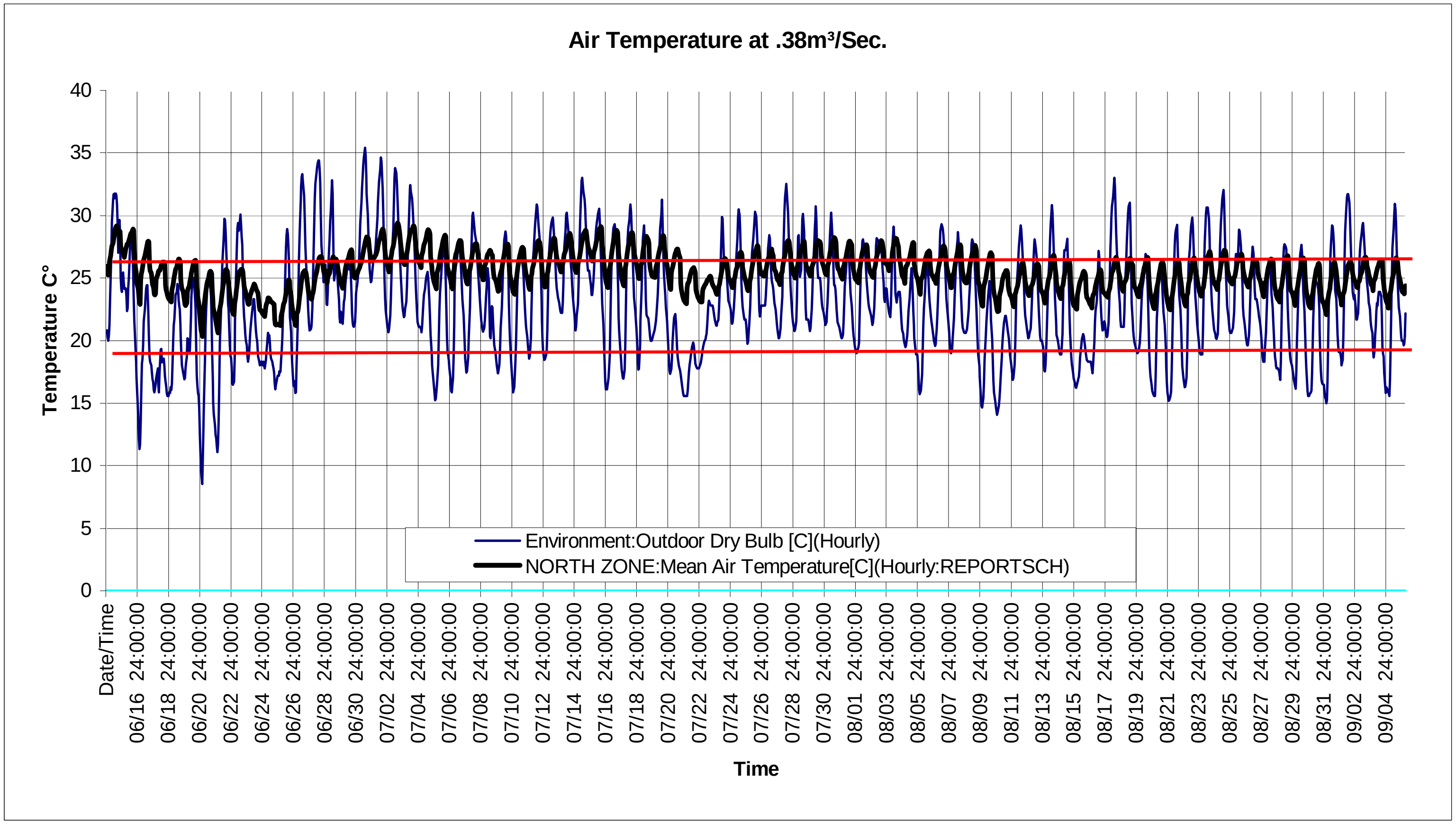
Where;

Overheated period: the time where air temperature is more than 25C° and the relative humidity is more than 75%.

X= The maximum outside indirect air ventilation rate (m³/Second) which will be allowed and controlled by the outside air controller.

Table 5- 1: Air comfort under Indirect ventilation rate of .38m^3/Second.

Ventilation Rate of .38m3/Second	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26	533.00	648.00	569.00	790.00
Number of Under Heating Hours with temperature<18	183.00	0.00	0.00	0.00
Total Number of Hours simulated	2000.00	2000.00	2000.00	2000.00
percent of over Heating hours %	26.65	32.40	28.45	39.50
percent of under Heating hours %	9.15	0.00	0.00	0.00
percent of cofortable air temperature hours %	64.20	67.60	71.55	60.50



Thermal comfort

Figure 5- 8: Air temperature under Indirect ventilation rate of .38m³/Second.

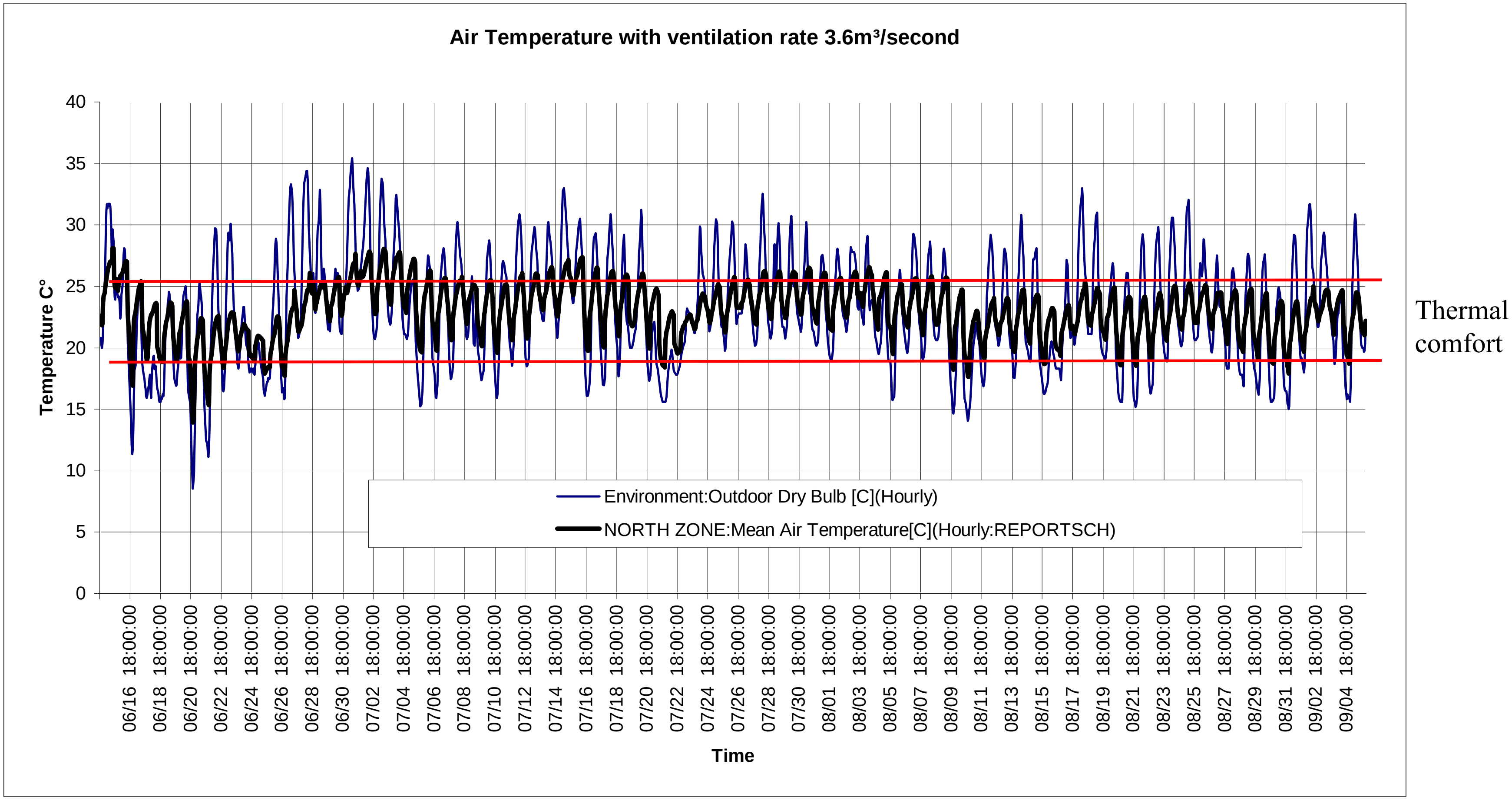
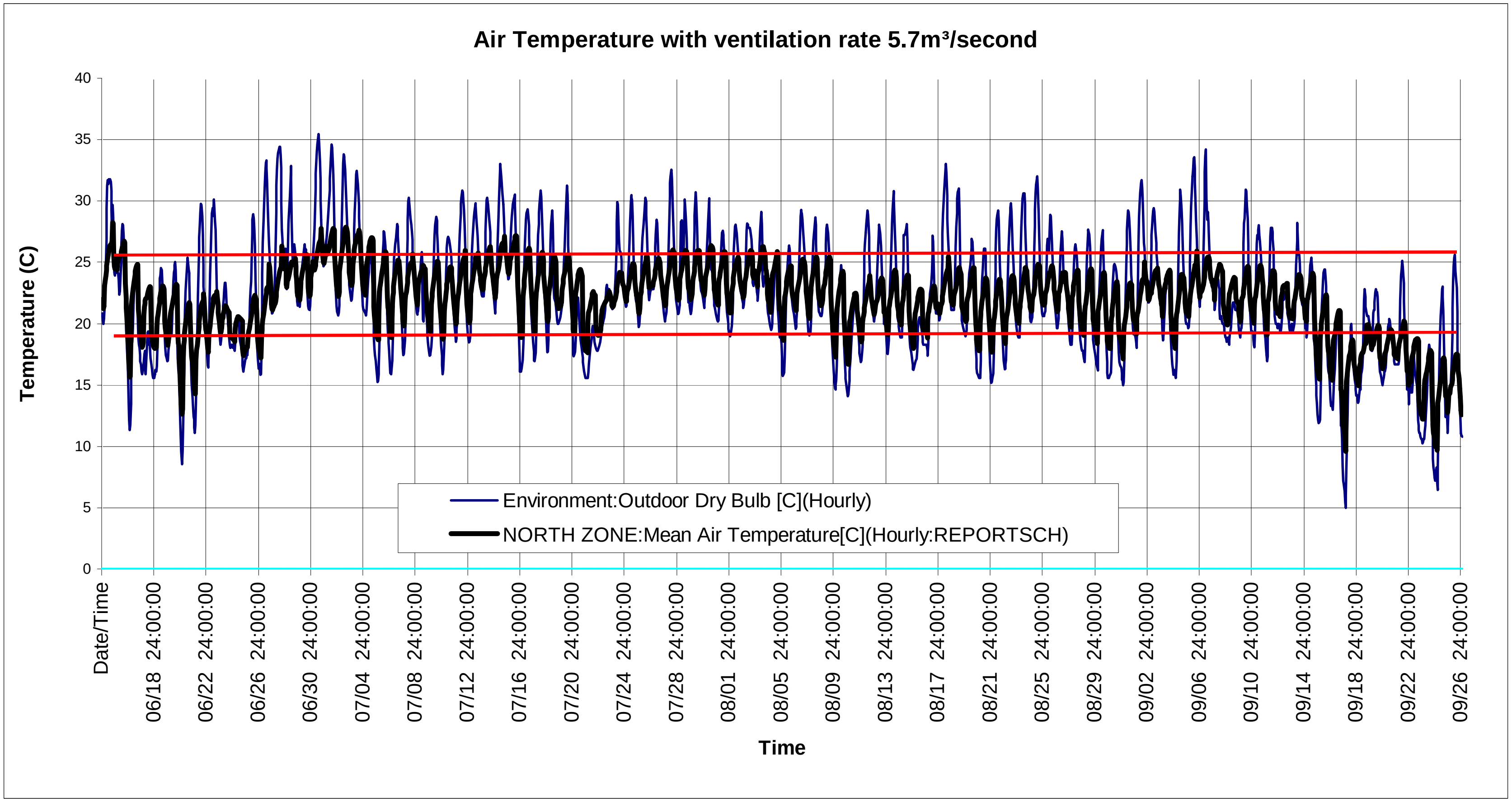


Figure 5- 9: Air temperature under Indirect ventilation rate of 3.6m³/Second**.**



Thermal comfort

Figure 5- 10: Air temperature under Indirect ventilation rate of 5.7m³/Second.

Table 5- 2: Air comfort under Indirect ventilation rate of 5.7m³/Second.

Ventilation Rate of 5.7m3/Second	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26 C	533.00	206.00	357.00	101.00
Number of Under Heating Hours with temperature<18 C	183.00	23.00	21.00	18.00
Total Number of Hours simulated	2000.00	2000.00	2000.00	2000.00
percent of over Heating hours %	26.65	10.30	11.80	5.05
percent of under Heating hours %	9.15	1.15	1.05	0.90
percent of cofortable air temperature hours %	64.20	88.55	87.15	94.05

Table 5- 3: Air comfort under Indirect ventilation rate of 3.6m³/Second.

Ventilation Rate of 3.6 m3/second	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Over Heating Hours with temperature>26 C	533.00	233.00	262.00	150.00
Number of Under Heating Hours with temperature<18 C	183.00	13.00	13.00	12.00
Total Number of Hours simulated	2000.00	2000.00	2000.00	2000.00
percent of over Heating hours %	26.65	11.65	13.10	7.50
percent of under Heating hours %	9.15	0.65	0.65	0.60
percent of cofortable air temperature hours %	64.20	87.70	86.25	91.90

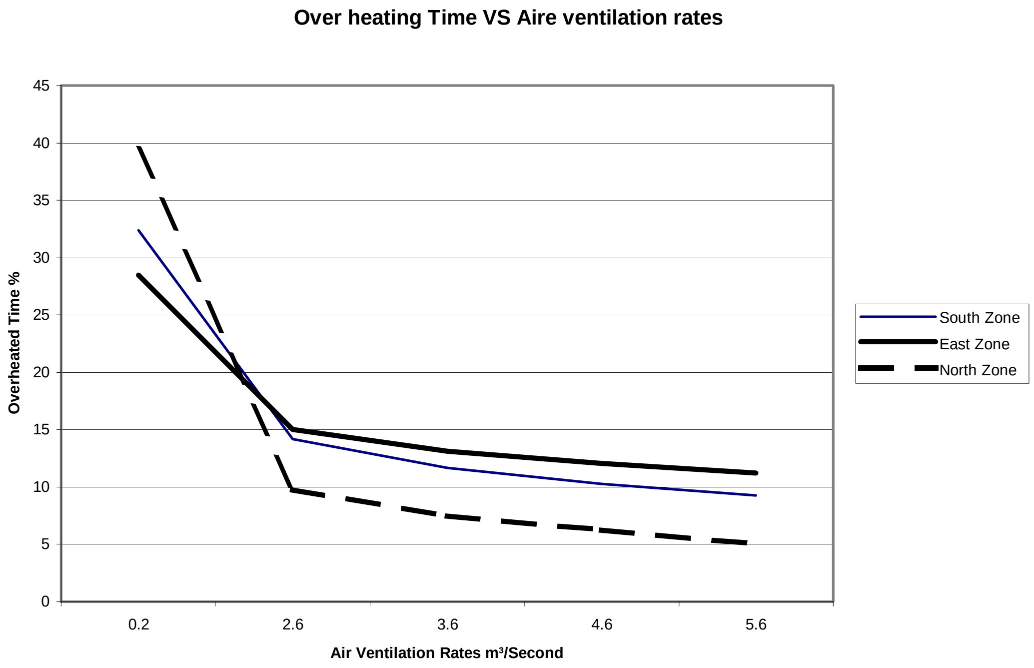


Figure 5- 11: The relation between indirect ventilation rates and the overheated periods.

Table 5- 4: Regression analysis between outside air ventilation rates as independent variable and overheated period as dependent variable.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.999511906
R Square	0.99902405
Adjusted R Square	0.998698734
Standard Error	0.745006156
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1704.470217	1704.470217	3070.928428	1.29437E-05
Residual	3	1.665102516	0.555034172		
Total	4	1706.13532			

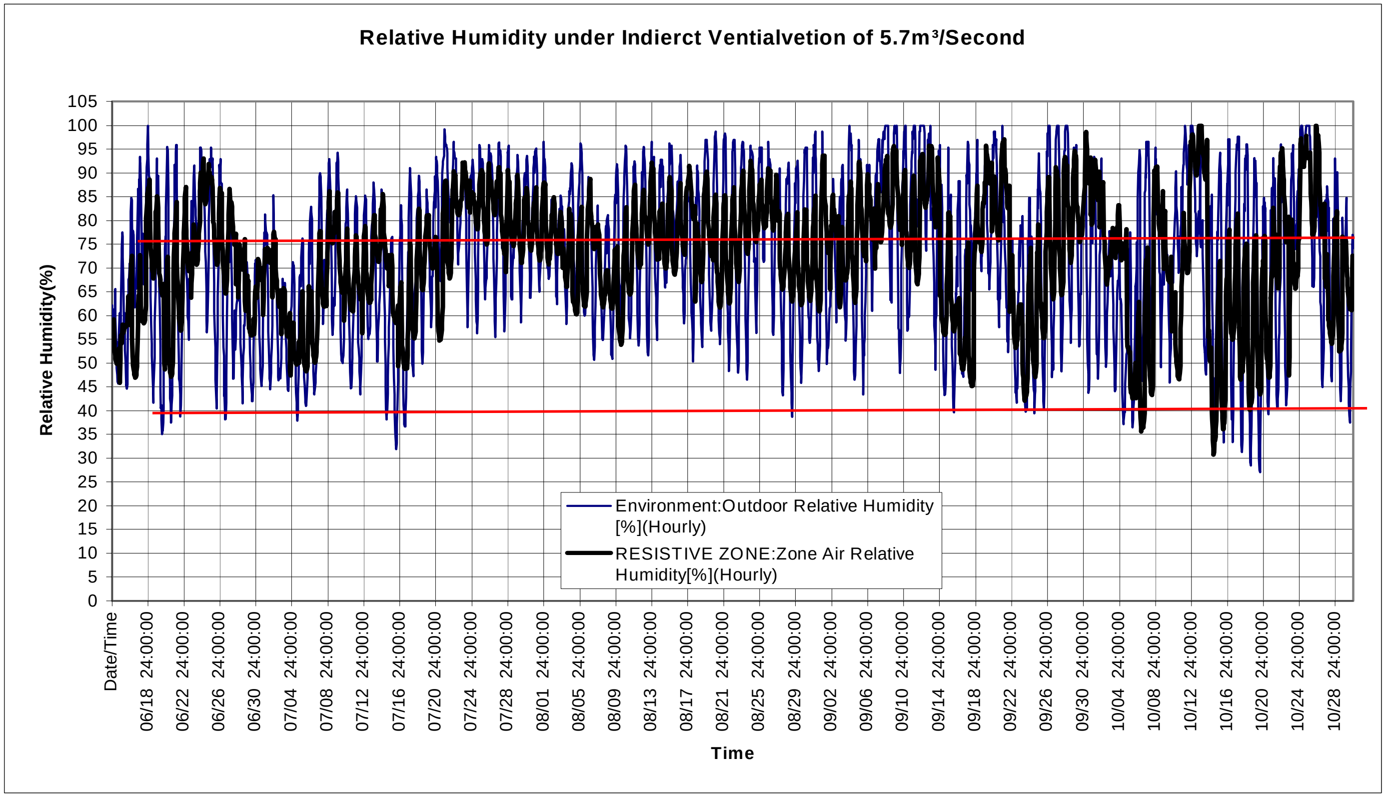
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	34.17456664	0.683634669	49.98951663	1.76282E-05	31.99893397	36.3501993	31.99893397	36.3501993
X Variable 1	-9.964026095	0.179804273	-55.41595824	1.29437E-05	-10.53624408	-9.391808113	-10.53624408	-9.391808113

5-6-2 Humidity control;

The simulation results showed that the current latent cooling load of the Beliveau house was accounted for 55% of total cooling load. Although indirect ventilation produced significant increase in air temperature comfort, relative humidity in the house was above 75% for 44% of the overheated period(Figure 5-12).

The proposed cooling by direct ventilation and indirect ventilation through heat exchanger were used to control both temperature and humidity. EnergyPlus© simulated the heat and moisture transfer in the house. Moisture Transfer Function (MTF) was selected for the moisture calculations. This solution algorithm calculates the simultaneous heat and mass transfer with vapour absorption taking place in the building construction.

Since EnergyPlus does not have air moisture content controller, the Outside air controller in EnergyPlus was set to control direct air flow rate with enthalpy limit of 50000 J/Kg(Hourly), which is approximately equivalent to air temperature of 21C° and relative humidity of 70% .



Thermal comfort

Figure 5- 12: Relative humidity under indirect ventilation rate of 5.7m³/Second.

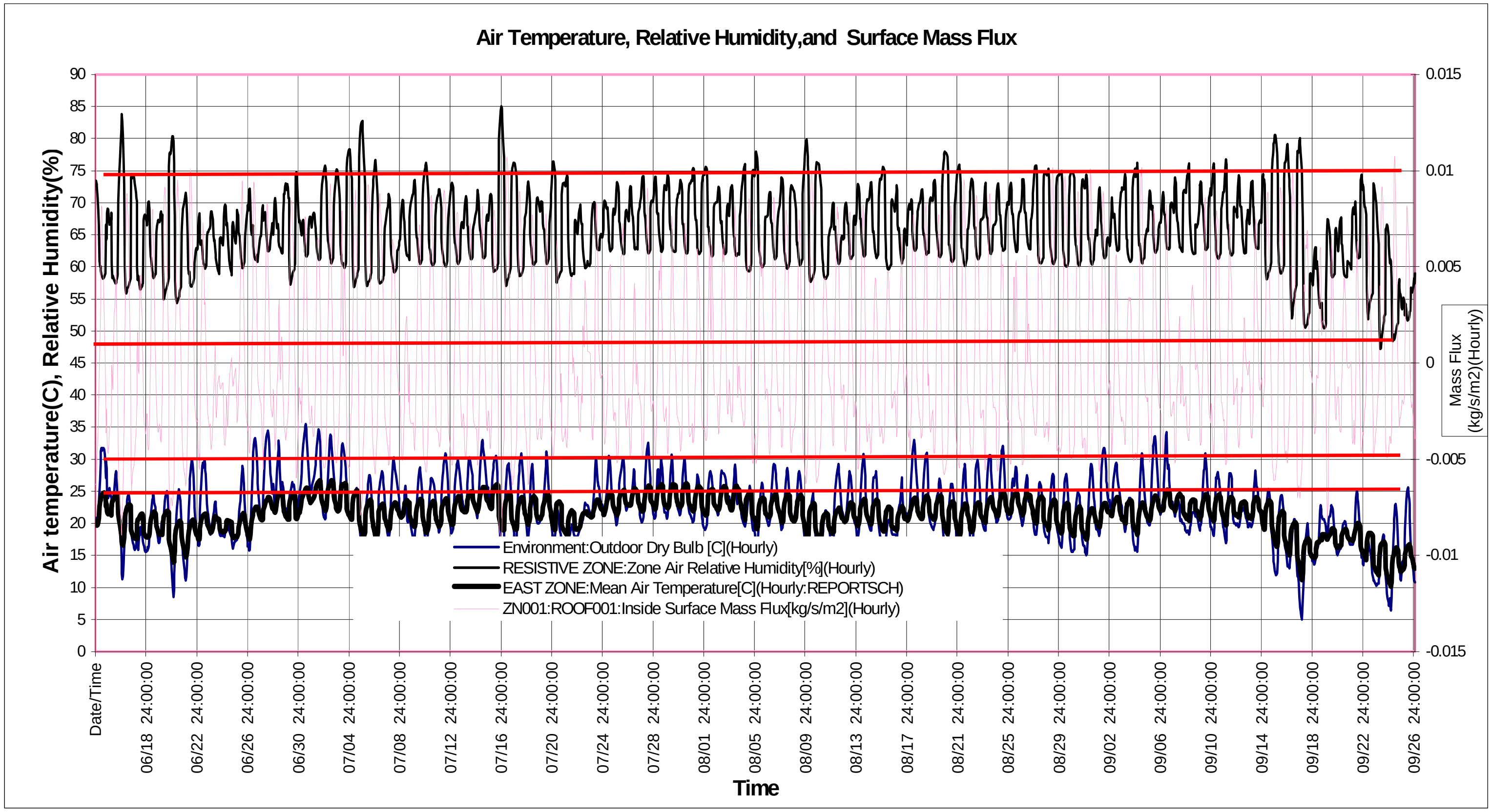
A combination of indirect ventilation rate of 5.7 m^3/sec and controlled direct air ventilation through a heat exchanger of 1, 3, 6, 9, 12, and 15 air change per hour (.38-5.7 m^3/sec) was simulated.

The simulation results showed that with controlled direct ventilation rate through heat exchanger of .6m^3/sec and indirect ventilation rate of 5.7 m^3/sec the house maintained a relative humidity of 75% or less for 93.8%, 93.5% and 93.2% for the north, east, and south zones respectively. At the same time, relative humidity was over 45% throughout the entire overheating period (Figure 5-13) (Table 5-5).

The simulation results also showed that with controlled direct ventilation rate through heat exchanger of 5.7 m^3/sec and indirect ventilation rate of 5.7 m^3/sec the house maintained a relative humidity of 75% or less for 98.8%, 98.5% and 98.5% for the north, east, and south zones respectively. The relative humidity was below 45% or less for 15.2%, 16.1%, and 16.0% for the north, east, and south zones respectively. However relative humidity was over 30% for 99% of the entire overheating period (Figure 5-14) (Table 5-6).

Although the relative humidity of less than 45% is not necessary for comfort feeling, it is vital for reducing mildew growth in buildings as we discussed early in the literature review. Also, since providing comfort air temperature requires higher air ventilation rate than that which is required to provide comfort relative humidity as the results showed, the appropriate direct, indirect and direct air ventilation rates are determined at Beliveau house by air temperature.

This simulation results suggest that implementing integration strategy of the direct, indirect, and direct air ventilation through heat exchanger to control both air temperature and relative humidity does not require more energy than indirect natural ventilation. Thus it enhances thermal quality of space and save energy without extra running cost.



Thermal comfort

Figure 5- 13: Moisture, temperature, and internal surface water mass flux under controlled air flow rate of up to .6m³/Second at Beliveau House .

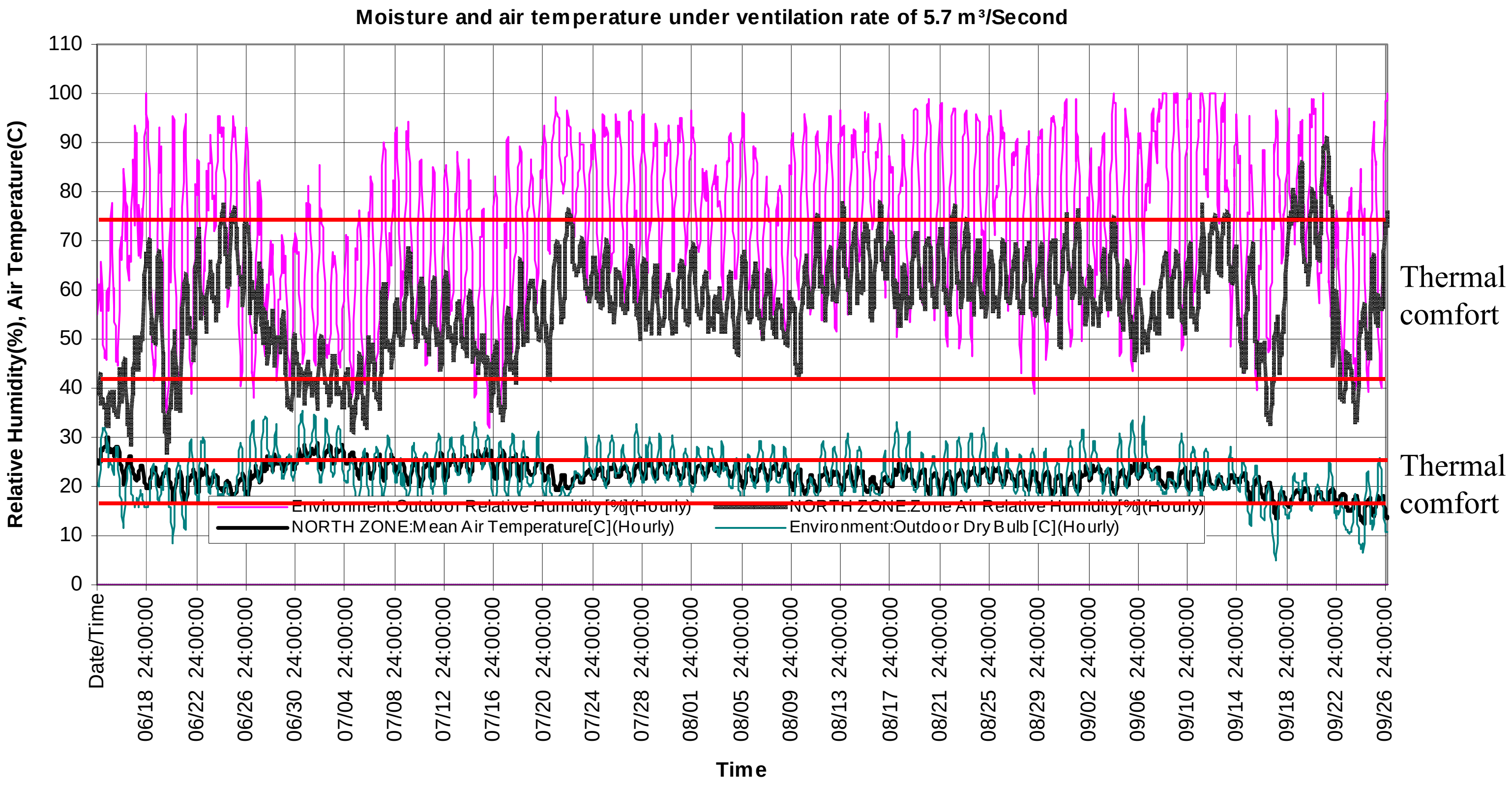


Figure 5- 14: Moisture and temperature under air flow rate of 5.7m³/Second at Beliveau House .

Table 5- 5: Relative humidity under direct ventilation of .6m/sec.

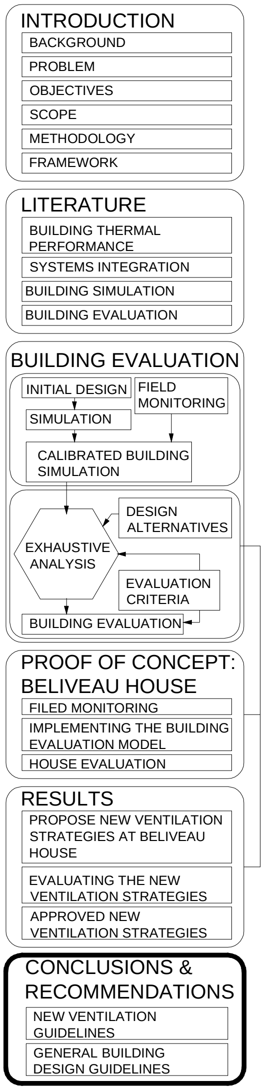
	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Hours with RH >75	944	135	129	122
Number of Hours with RH <45	91	0	0	0
Total Number of Hours simulated	2000	2000	2000	2000
Ratio of Hours > 75% RH	47.2	6.75	6.45	6.1
Ratio of Hours <45% RH	4.55	0	0	0

Table 5- 6: Relative humidity under controlled ventilation rate of 5.7m^3/Second at Beliveau House.

	Environment	RESISTIVE ZONE	EAST ZONE	NORTH ZONE
Number of Hours with RH >75%	944	29	29	25
Number of Hours with RH <45%	91	319	321	304
Total Number of Hours simulated	2000	2000	2000	2000
Ratio of Hours > 75% RH	47.2	1.45	1.45	1.25
Ratio of Hours <45% RH	4.55	15.95	16.05	15.2
Average Rh	617	72.88	51	52

Chapter Six

VI: CONCLUSIONS AND RECOMMENDATIONS



VI Conclusions and recommendations;

Issues of thermal evaluation regarding energy optimization are not fully considered during the design, in most cases. These issues rely on the holistic understanding of building thermal behaviour, which depends on the interaction of building elements with outside and inside variable conditions. The understanding of such interactions is based on the interpretation of complex simulation figures that rely on the nature of load generation and building configuration, as well as the field monitoring of a particular building. In the absence of advanced building energy evaluation tools, designers rely either on general thermal design guidelines principles or revert to intuitive methods which are not backed with sufficient knowledge to formulate their concept. This intuitive method is rarely lead to optimal energy efficient solutions.

This research introduced a methodology to predict and evaluate the holistic buildings energy performance, and implement these methods by developing an evaluation model which can test, simulate, evaluate, and aid in thermal design decisions. The new evaluation method provides a holistic picture of the actual contribution of major building elements on energy consumption.

The evaluation model results was tested and used to explore the energy saving by introducing new air ventilation strategies. These new approaches of utilizing natural ventilation are based on integrating direct and indirect air ventilation, and make air ventilation more efficient and applicable in locations with high humidity rates, high outside pollution rates, or very low nighttime air temperature.

6-1 Findings;

This research findings falls under three topics; first is introducing new building evaluation methodology, and second is deriving relations between the major building components. Third, on the light of the evaluation model results, the research introduced new air ventilation strategies to reduce both sensible and latent cooling loads, enhance indoor air quality, and elevate the thermal quality in buildings.

The research findings can be furthered explained as follows;

6-1-1 Building Evaluation;

There are no complete simulation, optimisation or evaluation models. It is clear that the energy simulation, optimisation, and evaluation models cannot make appropriate design decision on behalf of the designer. The designer only is capable of making these designs decisions. However, when designers are supported with appropriate evaluation tools which help in building a holistic picture of a particular design problem, designers can build strong intuitive feel and will be able to make more reasonable and accurate decisions.

We should remember that the pioneer architects such as Leonardo Da-Vinci spent most of their times and efforts in researching the math and science which support architecture before declaring that they are capable of producing sound architecture .

Further more, rules of thumb and general design guidelines cannot supplement the required science and knowledge needed in order to produce appropriate architecture. Unlike the existing simulation and optimisation model which either simulate building's performance or suggest "optimum" solutions. this evaluation model provides comprehensive analysis and data presentation, which unveils the holistic picture of the integration and interaction between the main building components. The model also validates that many relations between building design variables and its effect on building energy performance, which have been derived in this research, could not have been obtained without the evaluation model exhaustive simulation and analysis.

With the evaluation model, the designer not only understands the effect of design decisions on building energy performance, but also he/she will be able to predict the effect of the tradeoffs between these design variables on the building energy performance.

6-1-2 Integrating thermal mass, thermal insulation, solar radiation;

This research introduced new approach to view the integration and interaction between the thermal mass, thermal insulation, solar radiation, and natural ventilation. Now designers can view these design variables from the following perspectives;

6-1-2-1 Thermal mass;

In this research, thermal mass is not seen as the sensible heating capacity of building materials only. Latent heat storage of building materials is important as well, especially in humid climates or in buildings where internal latent heat gain is high.

This research revealed in particular the interaction between thermal mass and solar radiation. Without solar radiation, thermal mass showed no energy saving. On the contrary, thermal mass can have negative effect on energy saving (Anderson, 1995).

This research also suggested new approaches to utilize the latent heat storage of buildings materials in order to reduce latent cooling load, reduce the indoor relative humidity and enhance the thermal comfort. The sensible and latent thermal storage is coupled with new approaches of direct and indirect ventilation strategies.

In addition, utilizing latent thermal storage in buildings has major effect on other design concerns such as reducing the mildew growth in buildings. However, measuring the effect of the latent thermal storage in reducing mildew growth in buildings is beyond the scope of this research.

The evaluation model revealed two levels of thermal mass effect on building thermal behaviour, the first is the effect of thermal mass in reducing the total heating and cooling load, and the second is to balance the need for the heating and cooling in moderate weather conditions.

While researchers addressed thoroughly the first effect of thermal mass, the second effect of thermal mass did not attract much of the researchers attention. This research revealed the importance of thermal mass in improving the space thermal quality, and increasing the times in which passive thermal control is achieved. Thus reducing the need for the HVAC short-term operation, and improving the building thermal quality.

6-1-2-2 Thermal Insulation;

The evaluation model concluded that thermal insulation is the most determining factor in building thermal performance. Predicting the appropriate amounts of thermal insulation is rather complex, because it is interacted with the other major building design elements. The evaluation model proved its capabilities of producing specific relations that reveals the actual effect of the thermal insulation on energy performance for the specific buildings.

6-1-2-3 Solar Radiation;

Solar radiation is the second determining factor in building thermal performance. This research highlights the distinction between controllable direct solar radiation gain and indirect solar radiation gain. Although thermal insulation has the main role in determining the building thermal balance point, the outside air temperature varies, thus, controlled solar radiation is the main design element that can respond to the outside air weather changes.

Further more, selecting building orientation, aperture size and location are important direct solar radiation control strategies as shown in the literature review. However, the research showed the significant impact of controllable window shades on controlling direct solar radiation, because it can control both direct and diffused solar radiation, and improve windows thermal insulation.

Solar radiation also showed direct effect on the heating and cooling load through the solar radiation heat gain, and indirect energy saving where thermal comfort can be achieved at lower air temperature if solar radiation exists.

6-1-3 Natural ventilation;

Direct nighttime ventilation has been seen as the only ventilation cooling strategy. However in relatively humid climates or in buildings with high latent heat gain, nighttime ventilation is severely restricted. In some cases, nighttime ventilation does not reduce the total heat content in buildings (latent and sensible heat), Instead, It replaces air with high sensible heat content with air that has high latent heat content.

This research introduced new ventilation strategies. Here, inside air temperature was not the main control parameter of air ventilation. Instead, enthalpy and air moisture content was the control parameters. This research proved that integrating direct ventilation, indirect ventilation through heat exchanger, and direct ventilation through heat exchanger reduces both latent and sensible cooling load. These new ventilation strategies are no longer called “nighttime” ventilation, because they can be applied as early as 7pm in the evening and continue to function all night till 11am in the morning.

Since the new air ventilation strategies use higher air circulation rates to cool buildings, better air quality will presumably be achieved. However further research is needed to measure the air pollution desorption and absorption.

6-1-3 Summary of the Beliveau House performance;

The following Figure 6-1 presents the relation between thermal mass, thermal insulation, solar radiation, and natural ventilation and the average heating and cooling load . The figure below emphasizes the findings that thermal insulation has the major effect on energy consumption. Solar radiation has the second major effect on energy consumption, thermal mass has the third effect on energy consumption, and finally, natural ventilation has the fourth major effect on building energy consumption.

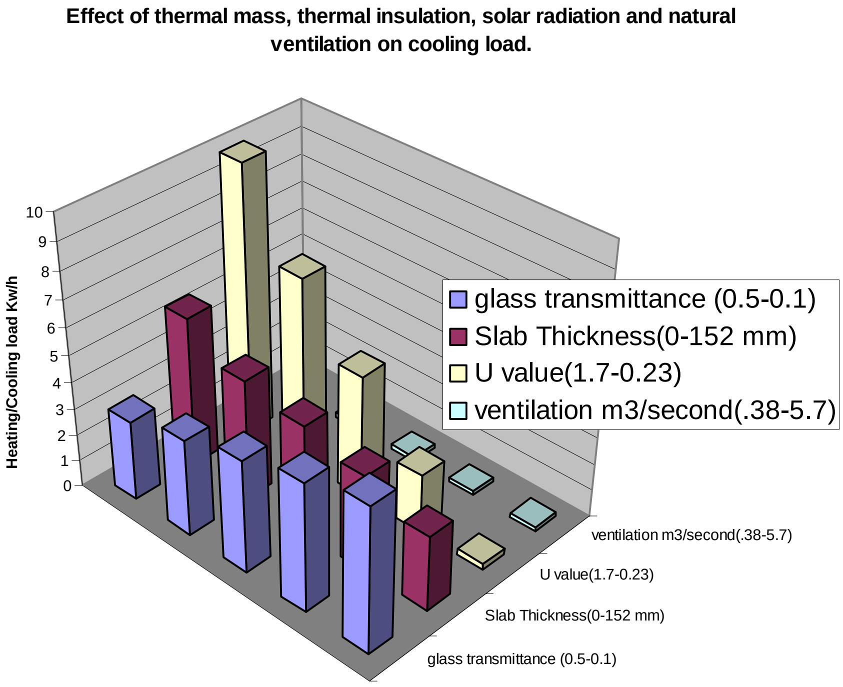


Figure 6- 1 : Effect of thermal mass, thermal insulation, solar radiation, and natural ventilation on heating and cooling load.

Figure 6-2 shows the overall passive thermal comfort , which can be achieved in both the heating and cooling periods of the Beliveau house after implementing the proposed energy conservation strategies.

As thermal insulation, thermal mass, controlled solar radiation, and controlled air ventilation increase, the potential for achieving passive thermal comfort increase.

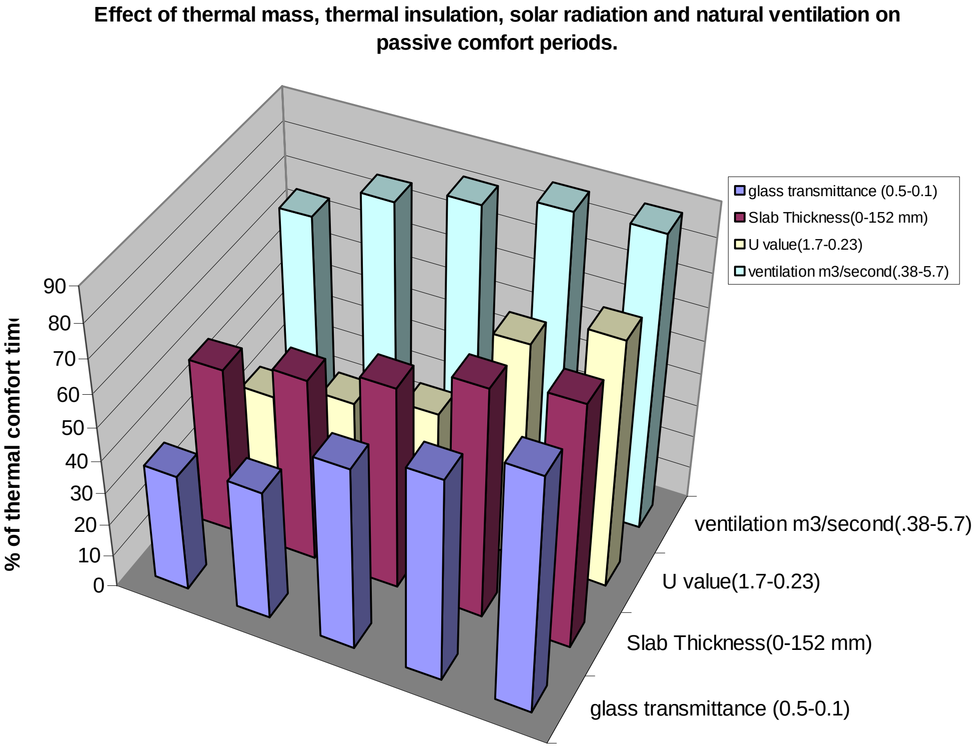


Figure 6- 2; The overall passive thermal comfort at the Beliveau house in both heating and cooling period.

6-2 Future research;

This research presents an evaluation model for designers that can be used to aid in thermal conservation and enhance thermal comfort in buildings. The model was tested and validated on residential building, and was used to reveal the relations between the thermal mass, thermal insulation, solar radiation, and natural ventilation. The model was also used to validate new ventilation strategies, which enhance the building thermal performance. To build on the findings of this research future research can be conducted on the following areas.

6-2-1 Holistic view;

In building evaluation, researchers have applied wide spectrum of evaluation techniques that ranges from applying simple mathematical relations to complex techniques such as neural network, optimization, and fuzzy logic. However, The designer is still the master of the decision making. Helping the designer in building strong intuitive feel by revealing the big picture of building performance will enhance the designer’s ability to make better design decisions. Therefore, building evaluation studies should empower the designer rather than supplement his rule. Empowering designers can be achieved by supporting them with the tools that reveal the integration and interaction between the different building components, as well as predicting in advance the consequence of the design decisions.

With the current computer revolution, processing exhaustive analysis and multi disciplinary advanced simulation is no longer a time consuming task. The available computation power can be used to provide multi-level data analysis and visualisation that simplify the understanding of building’s behaviour under different conditions.

This is the time where advanced building simulation and virtual reality presentation can be coupled to generate a virtual built environment of the anticipated building design. Then, designer as well as users can evaluate design alternatives as they witness them.

If the Stone Age ended for not the lack of stone, the current Oil Age will end also for not the lack of oil! . The sun is supplying the earth with much more energy than humans can use. We can say that energy required for heating buildings is the outcome of buildings imperfections. However, average temperature of the earth in most climate conditions is below or within the human thermal comfort requirement. Therefore, cooling is required as a result of mishandling the excess energy produced or admitted into buildings. Thus future research may focus on detecting the imperfections in buildings and solve them.

Passive thermal control in buildings is achievable. Much research proved this. However, selecting building variables and building components, which may achieve passive thermal control is integrated with other design elements. In most designs, selecting building components and configurations which do not support passive energy control is not a result of conflict between design requirements, but a result of insufficient information of the holistic building performance. Research may best serve the goal of energy conservation in buildings if it provides designers with a holistic picture of the building materials and components behaviour.

The current practice suggests that dehumidification can only be achieved through mechanical systems, However, this research proved that dehumidification can also be achieved by passive means. This research showed that selecting appropriate building materials along with building operation systems can insure healthy and comfort humidity levels in these buildings by passive means. To build on this, researchers should concentrate on the multi use of the building materials, and to rediscover the existing building materials and their use.

6-2-2 Building evaluation;

The proposed evaluation model is a core for larger implementations. More design variables and performance parameters may be included to increase its scope. The scope of the evaluation model can expand to include the following design parameters;

1. Thermal comfort parameters; enhancing the spaces thermal quality is as vital as energy saving. The acceptable thermal comfort parameters are also important factors in determining energy consumption in buildings. Incorporating comfort parameters such as air temperature, relative humidity, solar radiation, and air movement with the other building design elements can increase energy saving and improve thermal quality in buildings.
2. Indoor-air quality; The new ventilation strategies provide excellent opportunity to address the mildew problem in buildings. Controlling relative humidity below certain levels and for certain periods of time is the most effective solution to eliminate mildew in buildings. The new ventilation strategies also provide good opportunities to use the outside air to cool the space without admitting air

pollution-if exists- to the buildings or reduce the contaminants concentrations. However more studies is needed to incorporate the pollution concentration consideration in the new ventilation strategies.

3. Day lighting; Artificial lighting consumes considerable portion of energy in buildings. Recent simulation software facilitates integrating day lighting evaluation with building energy evaluation to save energy and enhance the quality of building spaces.
4. Cost benefit analysis; The proposed evaluation model may incorporate economic and cost-benefit analysis to provide the designer with a unified scale for evaluation. This scale may include the initial cost, running cost, and maintenance cost of buildings. This scale step up the proposed building evaluation model into an advanced level to run multi-disciplinary building evaluation.

This research provides a framework for a holistic evaluation model. The following developments can enhance the evaluation model results;

1. Advanced data visualization window; an advanced data visualization window will considerably enhance the building evaluation model results, and will provide multi levels of relations between the different sets of data.
2. Incorporate advanced analysis tools; Due to the limited time and resources, EnergyPlus© was used to simulate building energy performance. Other energy simulation tools may also be incorporated to simulate other building aspects such as lighting, sound, structure, management, and code compliance software.
3. This research used basic statistical analysis tools to derive the relations between the building design variables and the associated building performance. Other advanced statistical analysis tools can be integrated in the evaluation model. These analysis tools can generate advanced statistical relations such as neural network, and generic algorithm relations.

6-2-3 Cooling by ventilation;

This research proposed new ventilation strategies to reduce latent and sensible cooling load. To improve these ventilation strategies, the following research topics may be investigated further;

1. Integrating weather forecast data acquisition in controlling air ventilation; if climate condition is predicted in advance, charging or recharging the building sensible and latent thermal storage can be achieved more effectively.
2. Integrating naturally driven air ventilation; In high efficient buildings, the power consumed by fan is relatively significant. Naturally driven air ventilation through passive means such as double envelope, wind tower, and wind catchers may provide the required ventilation rates.
3. Integrating indirect evaporative cooling; In appropriate weather conditions, indirect evaporative cooling can be integrated with direct and indirect ventilation strategies to reduce sensible cooling load.
4. Integrating latent and sensible heat exchangers such as enthalpy wheel with the new ventilation strategies, especially in areas where outside relative humidity is higher than inside air humidity.

References;

Bibliography (referenced to it in research):

Abaza, H., Beliveau, Y. (2001); "New Approach for Utilising 3D-I Technology in Documenting Historic Buildings," Proceedings of the Archite

ctural Research Centers Consortium Spring Research Meeting Spring 2001, April 8-10, Virginia Tech, Blacksburg, VA.

Abaza, H., Beliveau, Y., and Jones, J. (2001); "Dehumidification Through Indirect Nighttime Ventilation," edited by S.J. Kleis and C.E. Bingham. Solar Engineering 2001, ASME—The 2001 International Solar Energy Conference, April 21-25, 2001, Washington, D.C.

Abaza, H., Beliveau, Y., and Jones, J. (2000); "Integrated Solar Radiation, Building Mass, Thermal Insulation, and Air Ventilation for Energy Conservation in Buildings," ROOMVENT 2000 Conference—Air Distribution in Rooms/Ventilation for Health and Sustainable Environment, pp 937-942, Reading, UK, July 9-12, 2000.

Abaza, H. (1999); "The effect of Traditional clothing on comfort feeling", Making Cities Livable Conference, Lindon, Germany.

Abaza, H. (1997); " A Scope For Developing human settlement in the Al- Badia Area In Jordan, An Architectural and Urban Dimension", International conference for desert development, Irbid, Jordan.

Akbari H.(1998). "Cool roofs save energy." ASHRAE transactions. Vol.104,part 1. p 241-247.

Al-Humoud,M., (1994). “Design Optimization of Energy Conserving Buildings Envelops” Ph.D. Research, Texas A&M University, USA.

Anderson I. (1995).” Heat storage in building thermal mass: A parametric study.” ASHRAE Transactions. Vol. 98, p 910-915.

Arlian, A., Chang, J. C. S., K. K. Foarde & D. W. VanOsdell (1996); "Assessment of fungal (*Penicillium chrysogenum*) growth on three HVAC duct materials." Environment International 22(4): 425.

ASHRAE, (1987); “ASHRAE handbook. Fundamentals”, American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

ASHRAE, (2001); “ASHRAE/IES Standard 90.1: Energy Standard for Buildings Except low-rise Residential Buildings.”, American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Azegami, Moriaki, **(1993)**. "Systematic Approach to Intelligent Building Design." IEEE-Communications Magazine. 31(10). 68-74.

BEANS (1997), “ BEANS building simulation manual” OASYS company, London, England.

BDA, (2000); “ Building Design Advisor.” Lawrence Berkeley National Lab, Internet Site : http://eandel.lbl.gov/BTP/BDA.

Bazjanac, Vladimir. (2001). "Acquisition of Building Geometry in the Simulation of Energy Performance," in Proceedings of Building Simulation 2001, pp. 305-312. Rio de Janeiro, Brazil, August 2001.

BEANS, (1997). " A Method to Predict Thermal Comfort at Any Point in a Space." Copyright OASYS Ltd., Developed by ARUP Research and Development, London, England.

Betzaida A. (1995). " Design of non linear HVAC control system with thermal load estimation." IEEE Conference on Control Applications Proceedings. Piscataway, NJ, p 33-39.

Bouriotis V. (19995). " Architectural design: Thermal performance and operational strategies of hypird solar building in Athens, Greece." Second Arab International Solar Energy Conference. P 167-172.

Brune, H., Betzaida A., (1997). "Design of non linear HVAC control system with thermal load estimation." IEEE Conference on Control Applications Proceedings. Piscataway, NJ, p 33-39.

Burch, H., (1997) "Investigation of Dynamic Latent Heat Storage Effects of Building Construction and Furnishings." ASHRAE Transactions. V 102, p 133-141.

Chang, J. C. S., K. K. Foarde & D. W. VanOsdell (1996). "Assessment of fungal (*Penicillium chrysogenum*) growth on three HVAC duct materials." Environment International **22**(4): 425.

Chen, P.,(1993) "NERGY saving Potential of Pre-cooling incoming Outdoor Air By Indirect Evaporative Cooling" Proceedings of the 1993 Winter Meeting of ASHRAE Transactions. Part 1. Chicago, II, USA, v 99, p 322-332.

Chin Y. (1995). " System approach to optimal control HVAC and building systems." Proceeding Of ASHRAE Annual Meeting. San Diego, CA. p 647-660.

Climate Consultant, (2002). “Graphically displays climate data software.” University of California at Los Angles, Internet Site : http://www.aud.ucla.edu/energy-design-tools/.

Collof, H. Godish, T. (1991). “Sick Buildings : Definition, Diagnosis and Mitigation”. Boca Raton, Lewis Publishers.

Crawley, B., Linda K. Lawrie, (2001). "EnergyPlus: New Capabilities in a Whole-Building Energy Simulation Program," in Proceedings of Building Simulation 2001, pp. 51-58. Rio de Janeiro, Brazil, August 2001.

Crawford, (1991) “Multivariate Statistical Analysis : A Conceptual Introduction” Book News, Inc. 1982.

David, H., Joseph K. (1993). “ Tests of an Electronic gateway to control an HVAC system.” IEEE International Conference on Consumer Electronics. Piscataway, NJ, USA. p 226-227.

Dickson, C., (1996). “ BREDEM: Testing Montly and Seasonal Versions Against Measurements and Against Detailed Simulation Models.” Building Services Engineering and Technology. V 17 n3 1996, p135-140.

DOE 2.1,(1997); Department of Energy Simulation Program, (1987). User Manual " DOE 2.1" Los Alamos, New Mexico.

Douglas, J., Balcomb, (1999). "Using *ENERGY-10*, to Design Low Energy Buildings". Internet Site: http://www.nrel.gov/buildings/energy10/resources.html.

EGYSAO (1997). “ EGYSO, Solar radiation simulation model manual” Istanbul Technical University, Maslak-Istanbul Turky.

Enebeder, Dounis A.(1997). “Knowledge-based versus classical control for solar-building designs” Applied-Energy. Vol. 50 n4, p281-292.

EnergyPlus.(2001). “EnergyPlus Manual: The official building simulation program of the United States Department of Energy.” Ernest Orlando Lawrence Berkeley National Laboratory.

EneryPro, (2001); “ Comprehensive energy analysis program”, Gabel Dodd/EnergySoft Inc. Internet site: http://www.energysoft.com.

ENER-WIN, (1995). “ Hourly Energy Simulation Program For Buildings.” University of Texas A&M, Internet Site; http://archone.tamu.edu/~energy/enerwin.html.

Fanger, P., (1973). Thermal Comfort and Applications in Environmental Engineering.” New York, Mc-Graw-Hill.

Fathy, Louts J., (2001) ” Spectacular Vernacular, A New Appreciation of Traditional Desert Architecture” Gibbs M Smith, Inc. Salt Lake City, USA.

Feustel H., (1992) ” Alternative to Compressor Cooling in Residences” Energy and Buildings, v18, p 269-286.

Fisher, Daniel E, (1999). "A Modular, Loop-Based Approach to HVAC Energy Simulation And Its Implementation in EnergyPlus," in Proceedings of Building Simulation ’99, Kyoto, Japan, September 1999.

Fletcher, A.,(1996).” Reduction in hlumidity as a method of Controlling Mites and Mite Allergens: The Use of Mechanical Ventilation in British Domestic Dwellings” Clinical and Experimental Allergy, V 26, p 1051-1056.

Foster, Nicolas J. (1996). “ An expert system: a versatile tool for the real-time control of solar building.” Journal-A. vol.33,no.3,p.99-105.

Gail A., (1998) "Thermal Adaptation in the Built Environment: A Literature Review" Energy and Buildings 27 p 83-96.

Givoni, Baruch.(1998). "Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Part I: 1993 experimental periods" Energy & Buildings. v 28 n 1 Aug 1 1998. p 25-32

Godish, T. (1995). "Sick Buildings : Definition, Diagnosis and Mitigation". Boca Raton, Lewis Publishers.

Hedrick, R.L.,(1998)." Development of a Humid Climate Definition**"** The Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, June 1998.

Heldebrandt W.(1998) " Assessing the impact of white roofs on building energy loads." ASHRAE transactions, Vol. 104,Part 1 p 353-361.

Heschong, L., (1979) "Thermal Delight in Architecture" The MIT Press, Cambridge, Massachusetts , USA.

ICAD, (1992) " Intelligent computer aided design" ICAD inc. London. UK.

Isetti, (1988). "Dehumidification Characteristics of Commercial Building Applications" Interim Report for ASHRAE 1121-RP. Civil, Environmental, and Architectural Engineering University of Colorado.

Jones, J., (1996) " Predictive Equations For Nighttime Ventilation Control Based on Building Mass Temperature" Ph.D. dissertation, University of Michigan, Michigan, USA.

Judkoff,R. (1994) " Procedure for Testing the Ability of Whole Building Energy Simulation Program to Thermally Model the Building Fabric." Solar Engineering-ASME-JSES-JSME-International Solar Energy Conference, New

York, NY, USA. P 341-352.

Kemp, S. J., T. H. Kuehn, D. Y. H. Pui, D. Vesley and A. J. Streifel (1995). "Filter collection efficiency and growth of microorganisms on filters loaded with outdoor air." ASHRAE Transactions **101**(1): 228.

Kirkpatrick, Isetti, C., (1988). " Predicting Vapor Content of the Indoor Air and Latent Load for Air-conditioned Environments: Effect of Moisture Storage Capacity of the Walls" Energy and Buildings, 12 p 141-148.

Klitsikas N., (1994) "Performance of an Indirect Evaporative Cooler In Athens" Energy and Buildings, v21, p 55-63.

Lee, Jaewook and Richard K. Strand. (2001). "An Analysis of the Effect of the Building Envelope on Thermal Comfort using the EnergyPlus Program," Association of Collegiate Schools of Architecture, Proceedings of the ACSA Technology Conference, Austin, Texas, 13-16 July 2001.

Messadi, (1994). "Comparison of the analysis of the useful net solar gain for space heating, zone-by-zone and for a whole-building" Renewable Energy. v 19 n 3 2000. p 435-442.

Mahdavi, A., (1995). "Effect of Lighting, Zoning, And Control Strategies on Energy Use In Commercial Buildings, " Journal Of Illuminating Engineering Society. 24(1) 76-79.

Malkawi, M., (1994). "Building Energy Design And Optimization: Intelligent Computer-Aided Thermal Design." Ph.D., diss., University of Michigan.

Markovic, S., (1993). "Mathematical Model of Heat Recovery in a Space-Heating and Ventilation System." Optimal Control Application and Methods. V18 n 1 Jan 1993, P47-61.

Masanori A. (1995). " Fuzzy logic and rough sets controller for HVAC systems." IEEE-WESCANEX-Communications, Power, and Computing. Vol. 1, p 133-138.

Mathew, P., (1996). "Integrated Energy Modeling For Computational Building Design Assistance (CAD)" Ph.D., diss., Carnegie-Mellon.

Meyer K. (1995). " Optimal control of an HVAC system using cold storage and building thermal capacitance." Energy and buildings, Vol. 23 n 1 , p 19-31.

Miller, b.,(1993). "Optimum design of the CSU Low Energy Building," ASME International Solar Energy Conference, Washington, D.C. 30-34.

Minoru K. (1995). " Hourly thermal load prediction for the next 24 hours by Arima, Ewama, LR, and artificial neural network." ASHRAE Transactions, n 1, p 186-200.

Mistry, S., (1993). " Non-Linear HVAC computations Using Neaural Network." ASHRAE Transactions. V 99, p 775-784.

Modera, M., (1995). " Improved Modeling of HVAC system envelope Interactions in Residential Buildings." ASME-JSES-JSME- International Solar Energy Conference. V 1 1995, ASME, New York, NY, USA. P 245-253.

Mohammadi, A. (1995). " Control and operational methodologies for energy=efficient operation of building HVAC systems", Ph.D thesis, The University of IOWA.

Mehdi, M. (1985). " Architecture in hot arid climates", Dar El-Nour, Sudi Arabia, 1985.

Messadi .(1994). “Role of thermal mass on the cooling load of buildings. An overview of computational methods” Energy & Buildings. v 24 n 1 1996. p 1-10.

Narendra K. (1996). “ Optimal control of HVAC systems using DDP and NLP techniques.” Optimal Control Application and Methods. Vol. 17 n 1 , p 71-78.

Obeidat S. (1995). “ Simulation model for defining three different solar accesses in site planning”. Simulation.v65 n 6 Dec 1995, p357-371.

Oseland A. (1998). “ Acceptable temperature ranges in naturally ventilated and air conditioned offices.” ASHRAE Transactions, Vol. 104, Part1.

Osman A. (1996). “ Application of general regression neural network (GRNN) in HVAC process identification and control.” ASHRAE Transactions. Vol. 102 n1, p 1147-1156.

Papamichael, K., (1997). "Building Design Advisor: Automated Integration of Multiple Simulation Tools," Automation In Construction. 6. 341-352.

Pedersen, C O, D E Fisher, (1997). "EnergyBase: The Merger of BLAST and DOE," in Proceedings of Building Simulation ‘97, Volume III, pp. 1-8, Prague, Czech Republic, 7-10 September 1997.

Peter J.(1990). “Integrated control system for low-energy buildings.” ASHRAE-Transactions, pt2. p 889-895.

Plathner, P., (2001), “ Modeling Water Vapour Conditions in Dwellings” University of Westminster, London, United Kingdom.

Ronald H., (1985). “ Environmental Control Principles, A textbook Supplement the AHRAE Handbook 1985 Fundamental Volume” ASHRAE, Inc. Atlanta, GA.

Samir, F., (1992). " Comupter Simulation of ARBS, Roof Color, Orientation and Wind Speed Effects on Ceiling Cooling Loads." ECOS'92 International Symposium." ASME, New York, NY, USA. P 689-695.

Santamouris, M., (1996). "On the Efficiency of Night Ventilation Techniques for Thermostatically Controlled Buildings." Solar Energy, June 1996 n 56(6), p 479-483.

Shaviv, E., (1990). " 1990 Annual Meeting of the American Society of Heating Refrigeration and Air-Conditioning Engineers." St. Louis, MO, USA. P 557-562.

SEMPER, (1997). "An Active Multi Aspect Architectural Design Support Environment," Internet address: (http://www.arch.cmu.edu/cbpd/semper/sember).

Simmonds, P., (1991). "Utilization and optimization of a building's thermal inertia in minimizing the overall energy usage," European Simulation Multiconference, Copenhagen (Denmark), 17-19 Jun 1991.

Simmonds, P., (1994)." Intelligent Building Design," Engineered systems, 11(6) 42-46.

SOLAR_5, (2002). Building Energy Simulation Software. University of California at Los Angles, Internet Site : http://www.aud.ucla.edu/energy-design-tools/.

Szokolay,S., (1980). Environmental Science Handbook" John Wiley & Sons, New York.

Stein, B., Reynolds, J., (1991). "Mechanical And Electrical Equipment For Buildings". John Wily & Sons, Inc. New York.

Strand, R.K., Crawley, D.B., C.O. Pedersen,(2000). "EnergyPlus: A New-Generation Energy Analysis and Load Calculation Engine for Building Design," Association of

Collegiate Schools of Architecture, Proceedings of the ACSA Technology Conference, Cambridge, Massachusetts, 14-17 July 2000.

Strand, R.K., and D.E. Fisher,(200). "Developing Thermal Intuition using Building Thermal Simulations in the Classroom," Association of Collegiate Schools of Architecture, Proceedings of the ACSA Technology Conference, Cambridge, Massachusetts, 14-17 July 2000.

Thomas W.(1998). "Effect of radiant and attic ventilation on residential attic and attic duct system: New tools for measuring and modeling." *ASHRAE transaction* ,Vol.104,Part1

Thomas W.(1998). "Effect of radiant and attic ventilation on residential attic and attic duct system: New tools for measuring and modelling." *ASHARE transactions* ,Vol.104,Part1

TRNSYS, (1995). " TRNSYS Building Energy Simulation Program." Internet Site: http://sel.me.wisc.edu/trnsys/downloads/download.htm

Yohanis, Y., (1999). " Utilization Factor for Building Solar-Heat Gain fro Use in A Simplified Energy Model." Applied Energy. V 63 n 41999, p 227-239.

Valen, Nt, (200) " Moisture Transfer in Organic Coatings On Porous Materials" Doctoral Thesis, Norwegian University Of Science And Technology, Trondheim, Norway.

Wang S. (1994). " Design, construction, and commissioning of building emulators for EMCS Applications." ASHRAE Transactions. Vol. 100 n1, p 1465-1473.

WINDOW 5.0, (2000). “WINOW 5.0 User Manual.” Windows & Daylighting Group Building Technologies Program, Environmental Energy Technologies Department, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA.

Winkelmann, F. C.(2001). "Modeling Windows in EnergyPlus" in Proceedings of Building Simulation 2001, pp. 457-464. Rio de Janeiro, Brazil, August 2001. .

Witte, Michael J., Robert H. Henninger,. (2001). "Testing and Validation of a New Building Energy Simulation Program" in Proceedings of Building Simulation 2001, pp. 353-360. Rio de Janeiro, Brazil, August 2001. .

Xiangdong H. (1995). “ Multivariable feedback design for regulating vapour compression cycles.” Proceeding of the American control conference. Vol. 6, p 4331-4335.

Xingdong H.(1995). “ Modelling of vapour compression cycle for advanced Controls in HVAC systems.” Proceedings Of The American Control Conference. Vol. 5, p 3664-3668.

Yao C. (1996). “ Methodology for optimal building heating dynamic operation.” ASHRAE Transactions. Vol. 102 n1, p 26-35.

Zaheer U. (1994). “ VAV system model for simulation of energy management control functions: off normal operation and duty cycling.” Energy Conservation And Management, Nov., p 917-931.

Zmeureanu, Radu, (1992). "Thermally Acceptable Temperature Drifts Can Reduce The Energy For Cooling In Office Building," Building Environment, 27(4), 40-42.

References (not referred to in research);

Al-Turki, A M. Gari, H N. Zaki, G M.(1997). “Comparative study on reduction of cooling loads by roof gravel cover” Energy & Buildings. v 25 n 1 Feb 15 1997. p 1-5 .

Aynsely, R., (1999). “ Estimitaing summer wind driven natural ventilation potential for indoor thermal comfort”, Journal of Wind Engineering and Industrial Aerodynamics, V 83, P 515-525.

Becker, Rachel. (1993). “Effects of heating patterns on internal surface temperatures and risk of condensation” Building & Environment. v 28 n 3 Jul 1993. p 333-345

Becker, R. Paciuk, M.(2002). “Inter-related effects of cooling strategies and building features on energy performance of office buildings” Energy & Buildings. v 34 n 1 January 2002. p 25-31

Bomberg, Mark. Brown, William.(1993). “ Building envelope and environmental control: issues of system integration” Journal of Thermal Insulation & Building Envelopes. v 17 Jul 1993. p 5-12

Boody, Harry.(1997). “Total systems design approach” ASHRAE Journal. v 39 n 8 Aug 1997. p 64-66, 68

Bouguerra, A. Prediction(1999). “Effective of thermal conductivity of moist wood concrete” Journal of Physics D-Applied Physics. v 32 n 12 1999. p 1407-1414

Braun, J E. Montgomery, K W. Chaturvedi, N. (2001). “Evaluating the performance of building thermal mass control strategies” Watershed Management Symposium - Proceedings. v 7 n 4 October 2001. p 403-428

Crawley, D B. Pedersen, C O. Lawrie, L K. Winkelmann, F C.(2000). “ EnergyPlus: Energy simulation program” ASHRAE Journal. v 42 n 4 April 2000 2000. p 49-56

Cunningham, M J. (1992). “Effective penetration depth and effective resistance in moisture transfer.” Building & Environment. v 27 n 3 Jul 1992 p 379-386

De Freitas, V P. Abrantes, V. Crausse, P. (1996). “Moisture migration in building walls - analysis of the interface phenomena” Building & Environment. v 31 n 2 Mar 1996. p 99-108.

Dahl, Scott D. Kuehn, Thomas H. Ramsey, James W. Yang, Ching-Hsu.(1996). “ Moisture storage and non-isothermal transport properties of common building materials” Hvac&R Research. v 2 n 1 Jan 1996. p 42-58

Deshmukh, M K. Sodha, M S. Sawhney, R L.(1991). “Optimum distribution of insulation over the walls and roof of an air-conditioned building.” International Journal of Energy Research. v 15 n 4 May-Jun 1991 p 275-288

Eftekhari, M M.(1998). “Natural ventilation: impact of wall material and windows on thermal comfort” Building Services Engineering Research & Technology. v 19 n 1 1998. p 43-47

Givoni, B.(1994). “Building design principles for hot humid regions” Renewable Energy. v 5 n 5-8 Aug 1994. p 908-916

Givoni, Kosny J.(1998). ” Performance check between whole building performance criteria and exterior wall measured clear wall R-value, thermal bridge, thermal mass, and air tightness. “ASHRAE Transactions. Vol. 104, part2.

Haeulp, P. Neue, J. Fechner, H.(1997). “Coupled heat, air and moisture transfer - the base of the durability of facade repair systems “ International Series on Advances in Architecture. v 3 1997. Computational Mechanics Publ, Ashurst, Engl. p 255-259

Hogan, John F.(1995). “Approach for opaque envelope U-factors for ASHRAE/IESNA 90.1-1989R” ASHRAE Transactions. v 101 n Pt 2 1995. ASHRAE, Atlanta, GA, USA. p 799-826.

Janinska, Barbara.(2000). “Environmental requirements for fungi” Proceedings of the Spe/Isrm Rock Mechanics in Petroleum Engineering Conference Journal of Thermal Envelope & Building Science. v 23 n 4 . p 339-348.

Medved, Saso. Novak, Peter.(1999). “Thermal insulation, shading and ventilation of transparent building envelope with a double cavity and siphon” Strojarstvo. v 41 n 1. p 19-26 .

Jayamaha, S E G.(1997). “ Heat and moisture transfer through building envelope components subjected to outdoor weather conditions including rain” Drying Technology. v 15 n 5 May 1997. p 1653-1656

Judkoff, R D. Neymark, J S.(1995). “ Procedure for testing the ability of whole building energy simulation programs to thermally model the building fabric” Journal of Solar Energy Engineering-Transactions of the ASME. v 117 n 1 Feb 1995. p 7-15

Keeney, Kevin. Braun, James.(1996). “Simplified method for determining optimal cooling control strategies for thermal storage in building mass” Hvac&R Research. v 2 n 1 Jan 1996. p 59-78

Katsman, Regina. Becker, Rachel.(2000). “Model for moisture-content evolution in porous building elements with hygro-thermal bridges and air-voids” Proceedings of the Spe/Isrm Rock Mechanics in Petroleum Engineering Conference Journal of Thermal Envelope & Building Science. v 24 n 1 2000. p 10-40

Khedari, J. Hirunlabh, J. Bunnag, T.(1997). “Experimental study of a roof solar collector towards the natural ventilation of new houses” Energy & Buildings. v 26 n 2 Sep 1997. p 159-164 .

Krusemann, Paul V E. Jansen, Jan A J.(1998). “Application of on-line thermal desorption-gas chromatography-Fourier-transform infrared spectroscopy-mass spectrometry for the characterisation of polymers” Journal of Chromatography. A. v 819 n 1-2 Sep 11 1998. p 243-248

Kurnitski, Jarek.(2001). “Ground moisture evaporation in crawl spaces” Building & Environment. v 36 n 3 Apr 2001. p 359-373

Kosny, J. Christian, J E. Desjarlais, A O. Kossecka, E. Berrenberg, L.(1998). “ Performance check between whole building thermal performance criteria and exterior wall measured clear wall R-value, thermal bridging, thermal mass, and airtightness" ASHRAE Transactions. v 104 n 2 1998. ASHRAE, Atlanta, GA, USA. p 1379-1389

Lotz, W A.(1998). "Insulation failure and moisture problems resulting from inadequate installation of insulation and/or vapor retarders" ASHRAE Transactions. v 104 n 2 1998. ASHRAE, Atlanta, GA, USA. p 1368-1372.

MacConnell, P F. Owens, D H.(1994). "Intelligent fuzzy regulation of residential buildings" Proceedings of the IEEE Conference on Control Applications. v 3 1994. IEEE, Piscataway, NJ, USA,94CH3420-7. p 1629-1634

Mahdavi, A. Lam, K P.(1993). "Dynamic analysis and visualization of water vapor diffusion through building components" ASHRAE Transactions. Publ by ASHRAE, Atlanta, GA, USA. v 99 pt 1 1993. p 288-296

Manzan, Marco. Saro, Onorio.(2002). " Numerical analysis of heat and mass transfer in a passive building component cooled by water evaporation" Energy & Buildings. v 34 n 4 April 2002. p 369-375

Meierhans, Robert A.(1996). "Room air conditioning by means of overnight cooling of the concrete ceiling " ASHRAE Transactions. v 102 n 1 1996. p 693-697

Miro, C R. Cox, J E.(2000). " Sustainable design and the high-performance building" ASHRAE Journal. v 42 n 8 August 2000 . p 24

Murtagh, A.(1996). "Effective efficiency" Insulation. p 18-19+21

Negrao, Cezar O R.(1998). "Integration of computational fluid dynamics with building thermal and mass flow simulation" Energy & Buildings. v 27 n 2 Apr 1998. p 155-165

Parker, D S. Sherwin, J R.(1998). "Comparative summer attic thermal performance of six roof constructions" ASHRAE Transactions. v 104 n 2 1998. ASHRAE, Atlanta, GA, USA. p 1084-1092

Price, B Andrew. Smith, Theodore F.(1998). “Optimal control strategies for HVAC and building systems under the influence of building mass” Proceedings of the International Conference on Energy and Environment, ICEE 1998. China Machine Press, Beijing, China.. p 194-204

Ribeiro, Rita Almeida.(1999). “Fuzzy evaluation of the thermal quality of buildings” Computer-Aided Civil & Infrastructure Engineering. v 14 n 2 Mar . p 155-162.

Rodriguez, E A. Allard, F.(1992). “Coupling COMIS airflow model with other transfer phenomena.” Energy & Buildings. v 18 n 2 1992. p 147-157

Roucoult, J -M. Douzane, O. Langlet, T.(1999). “Incorporation of thermal inertia in the aim of installing a natural nighttime ventilation system in buildings” Energy & Buildings. v 29 n 2 Jan 1999. p 129-133

Shaw, M R. Treadaway, K W. Willis, S T P.(1994). “Effective use of building mass” Renewable Energy. v 5 n 5-8 Aug 1994. p 1028-1038

Simmonds, Peter(1994). “Building envelope design” Engineered Systems. v 11 n 10 Oct 1994. p 50-56.

Simmonds, Peter.(1994). “Building envelope design” Engineered Systems. v 11 n 10 Oct 1994. p 50-56

Sodha, M S. Kaur, Jagjit. Sawhney, R L.(1992). “Effect of storage on thermal performance of a building.” International Journal of Energy Research. v 16 n 8 Nov 1992 p 697-707

Svennerstedt, Bengt.(1993). “Testing of settling for attic loose-fill thermal insulation” Journal of Thermal Insulation & Building Envelopes. v 17 Oct 1993. p 142-153

Svennerstedt, Bengt.(1995). “Analytical models for settling of attic loose-fill thermal insulation” Journal of Thermal Insulation & Building Envelopes. v 19 Oct 1995. p 189-201

Todesco, Giuliano. Super-efficient buildings: How low can you go? [Journal Article] ASHRAE Journal. v 38 n 12 Dec 1996. p 35-40

Uris, A. Llopis, A. Llinares, J.(2001) “The influence of **insulation** thickness and number of layers of gypsum wall board on lightweight partition sound transmission loss” Noise Control Engineering Journal. v 49 n 5 September/October. p 238-240.

Appendix 1

This appendix shows the thermal Performance of the Beliveau House under different design alternatives. The following charts are the results of the building evaluation. These charts show the Beliveau house performance under different building design alternatives which include different amounts of thermal mass, thermal insulation, solar radiation, and natural ventilation.

The charts shows the air indoor and outdoor air temperature, indoor relative humidity, and indoor solar radiation gain.