Characterization of Space Conditioning Loads for Energy Efficient Houses in Canada

by

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Abstract

This thesis details the development of a graphical method of presenting equipment loads within a house, allowing the loads for an entire year to be presented on a psychrometric chart. These charts are called rosettes. This graphical method allows the magnitude and distribution of both the sensible and latent loads to be examined, and for changes throughout the year to be examined. The rosettes can be used to determine whether or not conventional HVAC equipment is the best equipment for maintaining occupant comfort within the house, or if different equipment must be considered. This is of particular importance in highly energy efficient houses.

The rosettes also allow the split between the sensible and latent loads to be examined. In conventional houses, the loads are dominated by sensible loads, especially sensible heating. However, it is already known that energy efficient houses require supplemental ventilation to avoid the development of moisture problems within the house. It was expected that in a highly insulated house with both heat and moisture control equipment, the loads will be dominated instead by latent loads instead of sensible. In such houses, it was expected that supplemental moisture control equipment may be required. The rosettes were used to determine if this was indeed the case.

Simulations of six different houses were run using the program ESP-r, and the results were used to create rosettes for each simulation. The simulations examined different constructions, an increased number of occupants, the addition of active shading control, and the use of an alternative control scheme. The sensible and latent loads for each case are examined and discussed.

Rosettes produced from this study showed that improving the standard of construction has a significant effect on the equipment loads. However, the rosettes did not show a dramatic shift from sensibly dominated loads to latent dominated loads. The results show that changing the occupancy has the greatest effect on the equipment loads of the houses simulated in this study. The rosettes also show that while the shift from sensible loads to latent loads is not as dramatic as expected, there was a significant increase in the sensible cooling requirements

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Bart Lomanowski developed the CFC implementation as part of his master's work at the University of Waterloo, and was able to answer all my questions about how it worked. Bart also provided long-distance troubleshooting of ESP-r on several occasions, both for the CFC implementation and ESP-r in general.

There are also a number of close friends who deserve thanks for their support over the past three years. If I tried to list names I would leave someone out, but they provided food, help with moving, programming, beer, wine, couches to sleep on and shoulders to cry on. Without all their help and support I would not have decided to take on this project, let alone been able to complete it.

Finally, thanks to my parents, for everything.

Dedication

This thesis is dedicated to my parents.

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Nomenclature

Symbols

ω	Humidity ratio kg_{water}/kg_{dryair}
A	Area m^2
DD	Degree-days
FH	Amount of energy required for sensible heating for year $kWhrs$
h	Enthalpy kJ/kg_{dryair}
RH	Relative humidity %
U	U-value $W/(m^2K)$

Acronyms and Abbreviations

CaGBC	Canada Green Building Council
CDD	Cooling Degree Days
CFC	Complex Fenestration Construction
CHREM	Canadian Hybrid Residential End-Use Energy and GHG Emissions Model
CMHC	Canada Mortgage and Housing Corporation
CWEC	Canadian Weather for Energy Calculation
DHW	Domestic Hot Water
ELA	Estimated Leakage Area cm^2

EPA	Environmental Protection Agency
EPS	Extruded Polystrene
ERV	Energy Recovery Ventilator
ESNH	Energy Star for New Homes
HDD	Heating Degree-Days
HERS	Home Energy Rating System
HRV	Heat Recovery Ventilator
kWhr	Kilowatt hour
MMAH	Ministry of Municipal Affairs and Housing
MURB	Multi Unit Residential Building
NRCan	Natural Resources Canada
OBC	Ontario Building Code
REEP	Residential Energy Efficiency Project
RSI	R value in Systeme Internationale units
scfm	Standard cubic feet per minute
SHR	Sensible Heat Ratio
SNEBRN	Smart Net-Zero Energy Buildings Research Network
VLI	Ventilation Load Index
VOC	Volatile Organic Compounds

Chapter 1

Introduction

1.1 Background

In the past, air leakage and infiltration into a house through the building envelope was considered normal. Today, these old houses are expensive to maintain and heat. However, new homes built to be extremely energy efficient can encounter problems if there is not enough fresh supply air being brought into the house through mechanical ventilation. Air exchange, whether through infiltration or mechanical ventilation, is needed for the health and comfort of the occupants [Lstiburek, 2002, Harris, 2009]. Air exchange will add or remove moisture to the house, and there are many sources of moisture generation within the house itself. With an old, leaky house, the leaky building envelope dries out the house during the winter before the moisture causes any problems. In these houses the sensible loads are dominant, and latent loads are inconsequential. In new houses, moisture from inside sources and ventilation air is not allowed to escape as readily, and must be dealt with using mechanical equipment.

Energy efficient construction of houses in Canada has focussed on two things - increasing the thermal insulation, and reducing air leakage - to reduce the amount of energy the home requires in the first place. Renewable energy sources are becoming more popular, but are expensive, so in order for these to be effective, conservation must be investigated first. As the need for conservation has become more and more apparent, the Ontario Building Code and other building codes in use across Canada have been updated. Up to this point construction standards have focussed on reducing the sensible heating and cooling loads and on improving occupant comfort, and it is common knowledge that these benefits can all be achieved by adding thermal insulation and reducing air leakage [CMHC, 2012b].

However, very little work has been done to track the latent loads, either to characterize these loads or to examine how changing latent loads will affect the design of residential HVAC systems.

A home can be made “green” either at the time of construction, or through retrofits. Common energy efficiency measures include increased insulation, sealing of the building envelope, upgrades to windows and HVAC equipment, and the installation of energy efficient home appliances and lighting. New construction may also allow the location and orientation of the home on the building site to be selected for optimal performance. These improvements make the building more energy efficient, but they also affect the sensible and latent loads within the house.

The dominant space conditioning loads (i.e., equipment loads) in a conventionally built house are sensible loads, due to heat transfer through the walls, roof, windows, etcetera, and from air exchange through the building envelope. Air exchange also provides some or all of the fresh air to the interior, that comes into the house at outside conditions and then must be heated or cooled to meet the desired setpoints. As the envelope is improved and the rate of infiltration is reduced, space and equipment loads can be reduced significantly.

Current residential HVAC system design may not be appropriate for a house where the dominant loads are latent instead of sensible. Systems designed to provide sensible heating to conventionally built homes may be oversized or no longer appropriate, and humidity control equipment may become necessary to control the relative humidity within the home.

In addition to reduced equipment loads and reduced heating and cooling costs, better control of indoor air quality and understanding of the dominant loads within a space can have significant implications for the comfort and health of the occupants, as well as the durability of the structure. While excess moisture is generally not a problem in conventionally built houses in most of Canada, lack of fresh air supply is known to be a problem with air-tight houses elsewhere in Canada [CMHC, 2012b]

1.1.1 The Impact of Better Building Envelopes on Heating and Cooling Equipment

Currently sizing of humidification and dehumidification equipment in green houses is based on rules of thumb and best guesses, or by using the same equipment that is installed in houses that are just built to meet the building code. This can result in oversized or inappropriate equipment being installed in homes that are intended to be energy efficient.

In the past, oversized combustion equipment (i.e. too much peak capacity for the loads that are present) frequently operated under part load conditions, resulting in inefficient operation of equipment [CMHC, 2012a, McQuiston et al., 2005]. Inefficient operation meant that the equipment would cycle more frequently, consume more fuel, and potentially need more maintenance over time.

Larger capacity heating and cooling equipment generally costs more to purchase and install, in addition to increased fuel costs. If a homeowner is going to spend money on improving the envelope of their home, they should expect to save money elsewhere. To take full advantage of the potential cost savings from improved building envelope design and construction, small, efficient heating and cooling equipment should be used. This will also reduce fuel costs and other problems that may be associated with oversized equipment.

Currently, moisture problems (either too much or too little) are generally identified by the occupants after the house is occupied, and dealt with by purchasing off-the-shelf equipment such as humidifiers and dehumidifiers. These solutions are generally not energy efficient and may generate more problems for the homeowner. For example, use of a humidifier may cause condensation on the walls, and a dehumidifier may need to be emptied regularly. It is also up to the user to place this equipment in the correct location, and turn it on and off when necessary.

In old, leaky houses, there was enough air exchange through infiltration, and mechanical ventilation was not required. With increased focus on energy efficiency and occupant comfort, and increased stringency in building codes and air quality requirements, mechanical ventilation is now needed to maintain a healthy and comfortable interior environment in most new homes.

Opening windows can be used to provide air exchange, but this is not ideal in the Canadian climate. Air tight buildings will usually require the installation of a Heat Recovery Ventilator (HRV) or an Energy Recovery Ventilator (ERV) to provide fresh supply air to the conditioned space, while reducing the amount of energy that is required to heat or cool the house. Rather than supply fans alone, which draw air into the conditioned space at outdoor conditions, HRVs and ERVs pre-condition the supply air using waste heat from the exhaust air. HRVs provide only sensible heating or cooling to pre-condition the supply air, while ERVs provide both heat and moisture transfer between the supply and exhaust air streams within the unit.

1.1.2 Current State of Canadian and Ontario Housing Stock

There is a wide range of housing stock in Ontario, ranging from houses built prior to the year 1900 to brand new, energy efficient designs. Old housing stock is generally poorly insulated, and may not have an air barrier layer within the wall assemblies. If installed, the air barrier layer may be ineffective. No heat recovery equipment is installed. There may be some mechanical ventilation installed, but this is for indoor air quality in the kitchen or bathroom (i.e., exhaust fans). This mechanical ventilation may have been added as part of a retrofit, depending on the age of the house.

For this thesis, current housing stock includes any house that was built from the year 2000 onwards but not certified under a green building certification or incentive program. These houses are acceptably insulated, have an air barrier included in the envelope assemblies, and may or may not have heat recovery equipment installed. There will probably be some mechanical ventilation to provide supply air in addition to exhaust fans in the bathrooms and kitchens, and these exhaust fans will have been installed when the house was built.

Any house in Canada designed and built with reduction of energy consumption for space conditioning as one of the primary design objectives, regardless of the year the house was built, is considered to be energy efficient housing stock for this thesis. Certification under one of the many green certification or incentive programs is not a pre-requisite for being considered energy efficient. There are many reasons that a homebuilder might choose not to certify a project, and incorporating energy efficient design into a project should not be limited to projects that are intended for certification.

This thesis specifically examines detached housing where a single family is living under one roof. Attached housing refers to any structure where two or more housing units are connected under the same roof, and includes everything from duplexes to multi-storey apartment or condominium buildings. Basement suites and similar arrangements where a single family house has been converted into one or more apartment suites may also be considered attached housing. Attached housing will not be discussed further in this thesis as the number of variables that must be considered in these situations is outside the scope of this project. To give an idea of the scale of residential energy use, there are approximately 182000 homes in Kitchener-Waterloo and Cambridge, and about 56% of these are single, detached homes [CMHC, 2013]. The remainder is made up of semi-detached homes, duplexes, row housing or town houses, and apartments or condominiums.

For years there has been a trend towards improving energy performance in Canadian housing stock, driven by increasing fuel costs and concern about climate change. Since

2006, the cost of electricity in Ontario has increased from 7.5 cents per $kWhr$ to 11.4 cents per $kWhr$ for mid peak time of use at the end of 2014 [Ontario Energy Board, 2014]. The costs of other fuels commonly used for heating homes in Canada, such as natural gas and heating oil, have also increased.

In addition to the increasing cost of energy in Canada, energy use for residential heating and cooling represents a significant fraction of energy use and green house gas emissions in Canada [Natural Resources Canada, 2014b]. Space conditioning also represents a significant fraction of the total energy use for a single home, with space heating along representing approximately 60% of total residential energy consumption in 2011 [Natural Resources Canada, 2014b]. Space cooling makes up a much smaller fraction of energy consumption, but for energy efficient homes this proportion may increase. It is unknown whether the values shown in Figure 1.2 include energy consumed by humidification or dehumidification equipment.

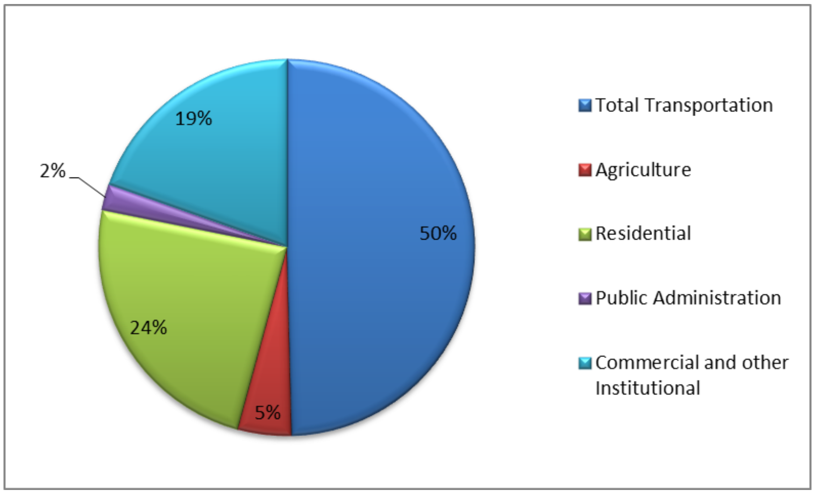


Figure 1.1: Breakdown of energy consumption in Canada in 2010 [Statistics Canada, 2012]

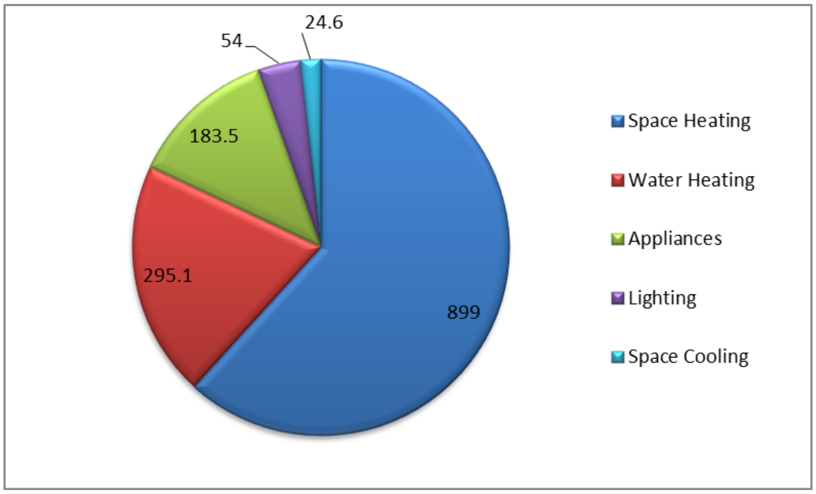


Figure 1.2: Canadian residential energy use by end use in petajoules in 2011 [Natural Resources Canada, 2014b]

1.2 Project Objective

The Smart Net-Zero Energy Buildings Research Network (SNEBRN) was assembled to research and develop strategies and technologies to achieve net-zero energy consumption, for both neighbourhoods and for individual homes and buildings. Net-zero buildings are buildings that produce as much energy through renewable sources as they consume. Reducing the equipment loads required within a house is an important part of achieving net-zero status.

This project has three objectives. The first objective is to develop a graphical method for examining the equipment loads of a house, and to show how this method can be used to compare the sensible and latent loads of different houses. The second objective is to determine if in high efficiency houses, the HVAC equipment loads are dominated by latent loads instead of the sensible loads that dominate in traditionally built houses. This will be done using the graphical method developed in the first objective. Finally, the graphical method will be used to determine if the climate where a house is located plays a key role in determining which loads are dominant.

The sensible and latent loads will be examined using building simulation software to run year-long simulations of several house models. The data from these simulations will be presented on psychrometric charts. The pattern formed by the data on the psychrometric chart has been named a rosette. These rosettes will be used to visually assess the HVAC requirements for the houses that were simulated. This information can then be used to develop effective HVAC system designs for energy efficient houses in the Canadian climate.

To meet the project objectives, three houses were modelled using ESP-r, a whole-building simulation program developed at the University of Strathclyde. All of the houses modelled have the same floor plan, site orientation, and occupancy. Each house was designed to meet different construction standards, one using a poorly built construction, one using current building codes, and one built to be extremely energy efficient. Four simulations of the energy efficient house were run to examine the effects of different factors that could influence the equipment loads within the house. Four additional simulations were then run using different locations within Canada to examine the effect of climate on the equipment loads.

The rosette plots were graphed for each simulation and examined. The information presented in the rosettes can then be used to determine if additional humidification or dehumidification will be required, and approximately how much capacity will be needed. This can in turn be used to design the house's HVAC system to be able to react to and handle the latent loads as well as the sensible loads. In addition, the Sensible Heat Ratio (SHR) for each timestep was calculated and plotted and the frequency of each load condition was examined.

1.3 Literature Review

1.3.1 Building Codes and Standards

The building code used in this study is the 2006 Ontario Building Code (OBC). Chapter 9 of the OBC applies to residential buildings, which includes multi-unit residential buildings (MURBS), low-rise residential buildings such as small apartment buildings, townhomes, and duplexes, single family homes, and cottages. Section 9.25 of the OBC covers heat transfer, air leakage, and condensation control in applicable buildings. The minimum thermal insulation for a house constructed according to the 2006 OBC is based on the number of heating degree-days for the location in Ontario where the house is to be constructed. The minimum levels of thermal insulation has increased over the years, reducing the sensible heating and cooling loads through the envelope. Greater understanding of thermal bridging within building envelopes has also led to reduced sensible heat loss through the envelope. Adding more insulation may reduce the air infiltration through the building envelope, but the OBC now requires that specialized air barriers be installed within the envelope. This requirement was added to the National Building Code of Canada in 1995 [Knight and Boyle, 2010]. This requirement is in the 1990 Ontario Building Code, and the section on air barriers was substantially expanded in the 1997 Code.

Air flow through an insulation layer will reduce the effectiveness of the thermal insulation, but this can be counteracted by the addition of an air barrier layer. The 2006 OBC requires the installation of an air barrier layer within the building envelope and includes a maximum air leakage characteristic in $L/s*m^2$ that this barrier material must not exceed. An air barrier is a material or assembly that does not allow air to cross it [Lstiburek, 2006]. The leakage rate of an air barrier layer must not exceed 0.02 $L/s*m^2$ [OBC, 2006]. This layer must be located within the assembly to prevent condensation in the walls during the winter. This air barrier may be installed in an exterior wall to prevent outdoor air from entering the conditioned space (e.g., in the walls and roof of a house), or between dwelling units in a MURB as part of the required fire and smoke separation between living units, and to prevent odours or other contaminants from entering adjacent units. The air barrier may also serve as a vapour barrier depending on the material, local climate, and type of construction assembly used [Lstiburek, 2006]. However, the 2006 OBC does not include any standards for the number of air changes per hour using a blower door test as detailed in CAN/CGSB-149.15-96 [CGSB, 1996]. Acceptable leakage rates around windows are provided.

Air barriers must be continuous over the entire surface of the building envelope, including around corners, at the intersections between the walls and the roof or the walls and the floor, around windows, doors, other penetrations, etcetera. Any gaps in the air barrier will result in air infiltration at that location so proper installation is essential for an air barrier layer to function properly [Harris, 2009]. A gap in the air barrier could be the result of improper installation, for example, not sealing all the joints between sheets of the air barrier material, or it could be the result of damage during construction.

A report commissioned in 2009 by the Ontario Ministry of Municipal Affairs and Housing lists recommendations for improving building envelope air tightness in the Ontario housing stock. The recommendations listed include improving the technical requirements for a material to be considered as an air barrier, and requiring more training for both installers and inspectors of air barriers. The houses studied in [Harris, 2009] showed that training alone resulted in a significant improvement in the air tightness of the envelope without adding to the material costs of the assembly.

1.3.2 Canadian Green Building Programs

As the need for more energy efficient homes has grown, many different programs to encourage energy efficient construction have been developed. LEED for Homes, EnergyStar, and R-2000 are the most common “green” certifications available in Canada today. Passive-House, a European standard that was developed in Germany in the 1970s has also certified some houses in Canada, though its stringent requirements mean that it is not as popular as other programs. All of these programs are voluntary certification programs that require a certified home builder and relatively extensive design and post-construction testing to achieve certification. None of these programs define occupant comfort when it comes to temperature and humidity within a home.

The programs discussed here also contain requirements for other energy conservation measures such as energy efficient domestic hot water systems, which are not discussed in this thesis but are important for the overall energy efficiency of the home.

LEED for Homes

The LEED for Homes designation is administered by the Canada Green Building Council (CaGBC), and was adapted from the LEED program as developed by the United States Green Building Council. LEED Canada has a number of different certification programs available for different building types. To obtain certification under LEED for Homes, a house must obtain a minimum number of credits in eight different categories ranging from the location of the home to educating the occupants and the general public about the importance of green building design. Sections 5 (Energy and Atmosphere) and 7 (Indoor Environmental Quality) are particularly relevant to the research in this thesis, as these sections deal directly with reducing the energy required for space conditioning in a home, while maintaining good indoor air quality. These sections will be discussed in more depth later in this section.

To be certified under LEED Canada for Homes, a house must meet a minimum energy performance of EnerGuide 76 or HERS 80. HERS stands for Home Energy Rating System, and both HERS and EnerGuide are rating systems used to grade the energy efficiency of a home. LEED credits are available for insulation levels that are above the minimum R-values or RSI values specified in the applicable building codes. The more thermal insulation added to the design, the more Energy and Atmosphere credits a project may earn towards the different certification levels.

Installing high performance windows, minimizing thermal bridging within the building envelope, and using energy efficient HVAC system designs all fall under the Energy and

Atmosphere section of LEED for Homes. Energy and Atmosphere LEED credits are also available for reducing the rate of air infiltration through the building envelope. To meet the prerequisites for LEED certification or to receive credit for reduced air infiltration, on site testing is required. The maximum infiltration rate allowable for each level of certification is based on the number of Heating Degree-Days (HDD) for the location of the house. The mandatory maximum level of infiltration ranges from 3.5 to 2.5 air changes per hour at $50Pa$, while the minimal envelope leakage option gives a maximum air infiltration rate of 2.5 to $1.5ach$ at $50Pa$ depending on the number of HDDs for the house's location as seen in Table 1.1. The greater the number of heating degree-days for the location, the lower the allowable air changes per hour from infiltration. The values presented in LEED for Homes do not represent a significant improvement over the current average air infiltration rates in Ontario as discussed in [Harris, 2009].

Table 1.1: Maximum allowable infiltration rates at 50Pa for LEED certification in homes in Canada [Canada Green Building Council, 2009]

LEED Criteria	**Zone A**	**Zone B**	**Zone C and D**
Reduced Envelope Leakage (Mandatory)	3.5	3.0	2.5
Greatly Reduced Envelope Leakage (Optional)	3.0	2.5	2.0
Minimal Envelope Leakage (Optional)	2.5	2.0	1.5

Section 7 of LEED for Homes, Indoor Environmental Quality, has several sections detailing different options available for LEED credits while maintaining a healthy, comfortable living environment. The section on Moisture Control is the most relevant to the research presented in this thesis. Outdoor Air Ventilation and Distribution of Space Heating and Cooling also provide insight into potential methods of saving energy, but will not be discussed in detail.

In Moisture Control, there are no prerequisites for LEED certification, in contrast to the requirements for thermal insulation or air infiltration, because there are no building code requirements for moisture control equipment to be installed in homes. One LEED point can be obtained for the project by installing dehumidification equipment to maintain an indoor relative humidity of 60% or lower. Appropriate dehumidification equipment will depend on the climate where the house is located. The LEED document emphasizes that dehumidification is not necessarily required or desirable in all situations, but it is up to the

HVAC contractor or designer to decide whether active moisture control equipment should be installed. A note in this section states that a moist outdoor environment will be the determinant of whether dehumidification is needed.

R-2000 Certification

The R-2000 standard for homes and buildings in Canada was developed in the early 1980s to encourage Canadians to purchase energy efficient, high performance homes. R-2000 is a voluntary certification program that applies to detached and attached houses Canada, as well as apartment and condominium buildings. It is a performance based standard and successful certification depends on the energy efficiency of the structure, not on meeting a set of prescriptive requirements. As such there is no minimum amount of thermal insulation specified under the R-2000 program, as long as local and provincial building codes are followed [Natural Resources Canada, 2012]. Certification under the R-2000 program requires a builder licensed by the program, a process that requires building and certification of a demonstration home. For certification the home must use less energy then conventional homes built in the same location, as well as the inclusion of other measures to make the home more environmentally friendly such as the use of low-Volatile Organic Compound (VOC) paints [Natural Resources Canada, 2012]. Specific energy consumption targets for a house to be certified are set using energy modelling with HOT2000.

EnergyStar and EnerGuide

The EnergyStar program was developed by the United States Environmental Protection Agency (EPA) in 1992, and some homes in Canada have been certified since 2005. It is an internationally recognized rating system that allows consumers and homebuilders to choose energy efficient home appliances, HVAC equipment, windows, and other products. Certification as an EnergyStar home requires similar features to certification under the R-2000 program, including upgrades to the building envelope and the HVAC system. Certification also requires that appliances installed in the home are also certified under the EnergyStar program. Design for local climate and independent testing is also required for a home to pass inspection and receive certification.

EnerGuide is a rating system used by Natural Resources Canada to compare the energy consumption of houses. It can be used for old houses or new houses. A house is given a rating on a scale of 0 to 100 based on its construction and operation. A rating of 0 is a poorly constructed home and 100 is a new, energy efficient house that is extremely energy efficient and operates using renewable energy only. The rating system takes into account construction, location, and site orientation, among other things. Old housing stock in Canada is rated at 0 to 50 if there have been no upgrades, an older house with energy efficient upgrades would be rated from 66 to 74, and a net-zero house would receive a rating of 100 under the EnerGuide rating system.

Unlike other programs discussed here, EnerGuide is not a set of requirements that a house must meet to receive certification. An EnerGuide rating shows the annual energy consumption of a home based on standard assumptions, and gives a method of comparing that energy consumption to other houses. Houses that appear similar at first may have very different ratings, allowing consumers to make informed choices about whether to purchase a particular house.

PassiveHouse

The PassiveHouse standard was developed in Germany in the late 1980s based on research from the 1970's and 1980's in Europe and North America, including findings from the Saskatchewan Conservation House, built in 1977 in Regina, Saskatchewan, as a demonstration project. PassiveHouse is a very stringent standard and as such is not as common in North America as other green certification programs, but there are projects in Canada that have achieved certification such as the Rainbow PassiveHouse duplex in Whistler, British Columbia. Unlike the rating systems discussed above, the PassiveHouse standard has strict prescriptive requirements for energy consumption for space heating, space cooling, and dehumidification, as well as electricity use [Passive House Institute, 2013]. The energy consumption requirements in the PassiveHouse standard are based on the floor area. The strict air tightness requirement of $0.6ach$ may not be exceeded regardless of the size of the house.

1.3.3 Related Work

In the past, research into energy efficient building designs has focussed on reducing sensible loads and peak electrical loads. This research has led to improvements in building codes and a renewed emphasis on conservation of energy, instead of reliance on green energy generation.

Previous work on the latent loads within a house is limited, apart from some work done on relative humidity levels and moisture control in homes in the southern United States [Harriman III et al., 1997, Lstiburek, 2002]. Even so, that work does not include analysis of the equipment loads associated with humidification or dehumidification, looking instead at the relative humidity levels within the house and whether the interior environment is considered comfortable (e.g., [Lstiburek et al., 2007]). One paper has been written on moisture generation rates within homes in Norway, but the application of the results presented in that paper is limited as the results focussed on the relative humidity levels [Geving and Holme, 2011]. Geving and Holme [2011] also acknowledges the wide variation in moisture generation rates.

Electrical Loads in Ontario Housing

[Pietila, 2011] focussed on reducing the electrical loads in a single family house located in Toronto, Ontario, and on shifting and reshaping the peak loads so that the electrical load profile no longer shows pronounced peaks. This was done by three different techniques - adding architectural features such as external shading, changing setpoints, and by changing behaviour of the occupants. Building simulations using the software ESP-r were undertaken to perform the work.

[Pietila, 2011] provides data on the electrical draws from different household appliances from a house in Toronto. The effectiveness of different energy efficiency measures at reducing or eliminating the electrical draw was examined, particularly at times of day when the Ontario electrical grid is experiencing peak loads. The data presented by Pietila [2011] shows the extent of the internal gains within a house due to appliances, lights, and other items in the house. As with the majority of the work examined, Pietila [2011] examined the sensible heating and cooling loads for the house, but did not consider the loads associated with maintaining a comfortable relative humidity within the house. The load reduction and peak shifting techniques also did not take into account the latent loads that some household appliances will create.

The Development of the CHREM

[Swan, 2010] details the development of the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) database. This database uses ESP-r and Natural Resources Canada (NRCan) data on nearly 17 000 houses from across Canada to provide a new model for greenhouse gas emissions and energy consumption in Canada. The CHREM applies only to houses and can be used to provide information on the energy requirements for space heating and cooling within the home, such as small appliances, domestic hot water (DHW), and lighting [Swan, 2010].

Swan [2010] uses estimates of the sensible and latent heat generated by the occupants of a house via their metabolism. This information, along with energy consumption statistics presented in [Swan, 2010] and those from [Pietila, 2011], were used to develop the occupancy and casual gain schedules used in the ESP-r simulations presented in this thesis.

Using ERVs to control SHR

Dieckmann [2008] uses building simulation software to examine the effect of installing Energy Recovery Ventilators (ERVs) in a medium size office building in the United States. The paper examines how the building load sensible heat ratio (SHR), the ratio of the sensible load to the total load, changed between 1975 and 2005 for buildings located in seven different climate zones. Dieckmann [2008] discusses the effectiveness of ERVs in the buildings studied. ERV units provide both heat and enthalpy exchange. Sensible heat transfer is accomplished through air to air heat exchange, while moisture transfer is achieved by the use of a rotary wheel type enthalpy exchanger. The SHR of enthalpy recovery equipment is able to automatically adjust to changing outdoor conditions [Dieckmann, 2008].

For all locations studied, the SHR of the building increased between 1980 and 1990, before dropping down below 1970 values after 1990. The maximum U-values for wall and roof assemblies showed a significant decrease from 1975 to 2000, and there was a decrease in both maximum solar heat gain coefficients of the windows installed and the maximum lighting power density in the office space. In line with the increase in computer use, the office equipment power density increased from 1975 to 2000.

Dieckmann compares the combined SHR of the cooling equipment installed in the buildings to the SHR to of the building cooling loads found from the building simulations. The combined SHR is the SHR of a system where a unitary air conditioner with a high SHR is combined with an ERV or other equipment with a low SHR. The building load SHR is the SHR of the loads generated at the conditioned space.

For the cooling load, three design conditions were studied: sensible design, latent design, and the shoulder seasons or part load conditions. Ideally, the SHR for the building load and the combined SHR should be very close for all three design conditions. The equipment and building SHRs were compared for the three design conditions for Miami, Florida, and Boston, Massachusetts. Location specific design conditions were selected for each of these cities. The Florida results show a very close match for both sensible and shoulder design conditions, but the Boston results show a mismatch for all three design conditions. This demonstrates that the sensible and latent loads, and which of these is the dominant, will depend on the local climate.

Of particular interest to the research undertaken for this thesis are the building load SHR data presented by Dieckmann. For all locations and all three design conditions, the SHR is constant between 1975 and 1980, and then between 1980 and 1990 the SHR is higher than previous years. In 1990, the SHR drops to 1970 levels or lower. Around 1998 there is a drop in SHR for all locations and design conditions, except for the sensible and latent design conditions for Albuquerque, New Mexico.

Latent Loads and Ventilation

Lstiburek [2002] examines circumstances under which moisture problems are likely to develop in the hot, humid climate of the southern United States. This was the only paper found that deals directly with the latent loads within houses, but this work cannot be applied to Canadian climate zones. This is also the only paper that was found that considered moisture problems caused by supplemental ventilation that has been installed to compensate for reducing the air infiltration across the building envelope. Potential moisture problems include mould, condensation on windows and other surfaces, and subsequent damage to building materials.

Lstiburek [2002] addresses the interaction between the building envelope and the HVAC systems within the house, focussing on homes located in the southern USA. The paper notes that the moisture within the house during the heating and cooling seasons, when the HVAC systems are operating frequently, is well-controlled, and the latent loads are not significant. During the shoulder seasons, there was a significant latent load when the indoor and outdoor temperatures were approximately equal. Air pressure differences caused by the operation of the HVAC system can also affect the infiltration and latent loads on the equipment.

According to Lstiburek [2002], houses in hot humid climates built to meet the current building codes or standards require supplemental dehumidification, especially during part-load or shoulder season conditions. The advantages and disadvantages of the different options available to provide dehumidification in a home with high indoor humidity in a hot humid climate are discussed. Off-the-shelf dehumidifiers are easy to find, low cost, and easy for the homeowner or occupant to install, but these dehumidifiers can be expensive to run and will add heat to the house, increasing loads on cooling equipment.

Appropriately sized enhanced air conditioning equipment or ventilating dehumidifiers are other methods of providing supplemental dehumidification [Lstiburek, 2002]. Both of these options must be sized properly for the house, and are much more expensive than an off-the-shelf dehumidifier. The paper comments on other work that shows that oversized air conditioning systems actually remove less moisture from the conditioned space.

Throughout [Lstiburek, 2002], the importance of correctly sizing HVAC equipment, regardless of its purpose, is emphasized. Correctly sizing and installing airtight ductwork and balancing air flow systems within the house will also reduce moisture problems that are caused by mechanical ventilation.

Ventilation Options in the United States

Lstiburek et al. [2007] examined a variety of ventilation options and their effectiveness in different houses in various climate zones in the United States. High performance houses and houses built to meet local building codes were simulated. For all cases appropriate levels of ventilation as per ASHRAE Standard 62.2 were used. The results presented in [Lstiburek et al., 2007] include frequency distribution plots of the hourly indoor relative humidities of each house during the heating and cooling seasons as well as the annual energy consumption, but no information is given on the heating and cooling loads associated with humidification or dehumidification.

Results from the simulated houses located in Houston, Texas, that were studied in [Lstiburek et al., 2007] were examined in detail in the section *Moisture Analysis*. In general higher performance houses had higher maximum relative humidity but relative humidity levels were also dependent on the ventilation system installed. High relative humidity was generally not dependent on the type of ventilation system, but on whether or not the cooling system was operating. During times when the cooling system was not operating, supplemental dehumidification was required for the Houston houses, regardless of the type of construction or mechanical ventilation.

The climate in Minneapolis, Minnesota, is similar to the Canadian climate, and some of the same trends seen in the Houston climate were also seen in Minneapolis. The higher performance houses had a high maximum relative humidity, regardless of what ventilation system was installed. The higher performance house in Minneapolis also shows many more instances where the relative humidity in the house was below 50%, possibly due to the longer heating season when cold dry air is brought into the house for ventilation. As with most work on this subject, Lstiburek et al. [2007] allows the relative humidity to free-float and does not include any information about the latent loads if a given range of relative humidity was to be maintained.

Airtightness of Ontario Housing Stock

The work presented in [Harris, 2009] was performed by Aubrey LeBlanc Consulting, Inc, and Diversified Services Group, Inc, for the Ontario Ministry of Municipal Affairs and Housing (MMAH) to determine average levels of infiltration in the current Ontario housing stock, and what methods were the most effective at reducing the air infiltration through the building envelope. This report also determined that achieving an infiltration rate of 2.5 air changes per hour at $50Pa$ was a reasonable goal for detached houses within Ontario. This represents a significant reduction in the average air infiltration rates in Ontario housing stock, but is still a much higher rate than the rates achieved in green homes across Canada.

In [Harris, 2009], blower door tests were performed on 81 single family detached homes and 19 attached homes across Ontario. Interviews with builders who were certified to build either R-2000 or Energy Star for New Homes (ESNH) homes were conducted to get a better idea of how the infiltration requirements for these standards were being achieved. All builders interviewed emphasized that careful design and installation of the air barrier layer is critical for achieving the requirements. The builders all identified transitions between different building assemblies as problem areas for air leakage.

The builders interviewed in [Harris, 2009] found that better training for workers involved in installing air barrier materials in building assemblies produced consistently better air tightness. Some builders also found that doing their own air tightness testing before completion of the building envelope allowed them to find and repair problems with the air barrier before the official blower door tests, giving better results on the official tests.

Airtightness of Canadian Housing Stock

In 1997 Natural Resources Canada released *Airtightness and Energy Efficiency of New, Conventional, And R-2000 Housing in Canada, 1997*, a report comparing the airtightness of homes of different eras and climate zones to the airtightness of R-2000 homes at the time [Natural Resources Canada, 1997]. More recent data from NRCan is not available. The report compares air infiltration rates for 163 new houses built to meet the building codes in effect between 1990 and 1996, data from 2037 houses built between the late 1700s and 1990, and 63 houses certified under the R-2000 standard. The R-2000 houses studied were constructed between 1983 and 1995.

Even in 1997, NRCan recognized the need for airtight homes to have mechanical ventilation installed to prevent air quality problems. At the time, most of the houses studied had exhaust fans installed in the kitchen and bathrooms, but none of the conventionally built houses had central ventilation systems. Levels of thermal insulation for the conventionally built houses and the R-2000 houses in the study were compared. In Ontario, the average air infiltration rate for houses constructed prior to 1920 was $16.1ach$ at $50Pa$ [Natural Resources Canada, 1997]. For houses from the same time period in British Columbia the average air infiltration rate was $26.6ach$ at $50Pa$. By 1991 Ontario and British Columbia infiltration rates had dropped to 2.8 and $4.3ach$ at $50Pa$, respectively. Infiltration rates for R-2000 certified homes are even lower. As the houses surveyed in [Natural Resources Canada, 1997] became more airtight, regional differences between measured air infiltration rates became less significant.

By 1997 it was already known that R-2000 homes were at risk of indoor air quality problems, and that HRVs offered a way of mitigating those problems. However, there was no mention of any moisture problems, either structural defects or occupant discomfort, in the report [Natural Resources Canada, 1997].

Adequacy of Natural Ventilation in Canadian Housing Stock

The Canada Mortgage and Housing Corporation (CMHC) provides information on the state of housing in Canada for homeowners, home buyers, builders, and governments. Research by the CMHC was carried out to determine how often natural ventilation was inadequate for providing fresh air to Canadian homes, and under what conditions [CMHC, 2008]. A survey of air exchange requirements to maintain indoor air quality was performed, and the minimum requirement for ventilation to maintain indoor air quality was found to be about 0.3 ach for most houses. This minimum may be met by infiltration, mechanical ventilation, or a combination of both, but [CMHC, 2008] only looks at air exchange that is met by natural ventilation. Underventilation is defined as "[...] the integrated total number of air changes less than those that would have been supplied by a constant ventilation rate meeting the 0.3 air changes per hour requirement" [CMHC, 2008].

In [CMHC, 2008], data for 8010 houses in two different cities were examined. Of those houses, 3848 were located in Ottawa, Ontario, and the other 4162 were located in Saskatoon, Saskatchewan. The houses in each location were classified by the era during which they were constructed, ranging from pre-1945 to 2004. For both locations the average number of hours from each era where houses were considered underventilated was tabulated. From the pre-1945 homes to the most recent homes, the number of hours each year where natural ventilation alone is not enough to provide the minimum supply of fresh air increases steadily for both Ottawa and Saskatoon. The newer the home, the more frequently supplemental ventilation is needed to maintain a healthy environment, due to increasingly stringent construction standards and building codes.

When natural ventilation is not adequate to maintain indoor air quality, mechanical ventilation is needed to supplement. However, [CMHC, 2008] notes that because natural infiltration is dependent on the outdoor environment, infiltration rates for the houses examined are higher during the winter. This may be enough to maintain air quality, but may mean higher heating costs. The circumstances under which the houses studied in [CMHC, 2008] are considered underventilated underscore the need for greater understanding of the space conditioning loads in homes, and for the HVAC systems installed in new construction to be designed and operated for the climate in which the house is built.

Effectiveness of Off the Shelf Dehumidifiers in Canada

[CMHC, 2009] examined whether or not stand-alone, off-the-shelf dehumidifiers are effective at controlling moisture within homes in various climate zones across Canada. During the first year of the two year study, relative humidity measurements were collected from 30 homes across Canada. In the second year, dehumidifiers were placed in 22 of those homes, and the relative humidity measurements were repeated (the remaining participants dropped out of the study for various reasons). In addition to measuring the outdoor and indoor relative humidity, the moisture levels of the wood used to frame the houses in this study were also recorded. The dehumidifiers were located in the basement, and were to set to turn on when a relative humidity of greater than 50% was detected. The dehumidifiers were emptied manually and would shut off automatically once the reservoir was full.

Overall, the dehumidifiers used in [CMHC, 2009] were effective at removing moisture from the basements where they were located and the main floor of the houses during the cooling season. Little or no difference in relative humidity levels was seen in the upper levels of the houses studied, further away from the dehumidifiers. Moisture removal rates and relative humidity levels were higher during the summer. Adding the dehumidifiers resulted in more consistent relative humidity levels in the basement throughout the year, especially during the summer months when the dehumidifiers were operating more frequently. However, home occupants are likely to open windows during the summer, so the dehumidifiers had little or no effect on the main floor of the houses during the summer [CMHC, 2009].

Retrofitting Existing Houses for Energy Efficiency

In addition to researching new technologies and characterizing the current state of Canadian housing stock the CMHC has performed retrofits on homes from various eras to inform homeowners and landlords on measures to save energy on space heating and cooling, and what savings can be achieved. An exterior retrofit and an interior retrofit for a house from the 1960's or 1970's were examined in depth.

The interior retrofit was able to achieve greater than 75% reduction in the energy required for space conditioning in a two story home built in the 1960s or 1970s [CMHC, 2012b]. This retrofit focusses on increasing the amount of thermal insulation in the house, as well as replacing the original windows and doors with high performance windows and doors. Even before the options for improvements to the thermal insulation are discussed in the document, it emphasizes the need to improve the airtightness of the building envelope from over $6.0ach$ to a goal of $1.0ach$ at $50Pa$. [CMHC, 2012b] emphasizes the importance of maintaining a continuous air barrier at connections between assemblies and around windows or other architectural features during renovations.

The CMHC technical highlight for the exterior retrofit of a 1960s or 1970s era bungalow [CMHC, 2012a] offers options for retrofitting the house for either 10% or 25% energy savings. Both options require that the air infiltration be controlled to reduce the loads on the house, and because air infiltration can reduce the effectiveness of any added insulation [CMHC, 2012a]. The houses discussed in this highlight were tested and found to have greater than $6.0ach$ at $50Pa$ prior to the renovations.

[CMHC, 2012a] focusses on the same methods of energy conservation as [CMHC, 2012b]. The exterior retrofit also includes a number of cautions if planning extensive retrofits as described in both case studies. This includes a warning that pre-existing issues with the house may become worse once the building envelope is improved, and that interior moisture sources must be controlled and the air barrier must be properly located within envelope assemblies to prevent moisture problems inside the assemblies themselves. The exterior retrofit highlight also warns that while energy consumption may be significantly reduced by increased insulation and reduced infiltration, the efficiency of heating equipment could be reduced since the equipment will then be oversized, and may be operating at part load and cycling frequently[CMHC, 2012a]. Resizing and possibly replacing heating equipment may need to be considered as part of the renovations detailed in the two case studies.

Both the interior retrofit and the exterior retrofit technical highlights emphasize the importance of making sure that sufficient air supply is maintained through the addition of mechanical ventilation to prevent problems with mould, indoor air pollution, and odours. The choice between the exterior or the interior retrofit is up to the homeowner since there are advantages and disadvantages to both. Other factors such as limitations of the distance of the home to property lines and historical significance may also affect what type of retrofit is possible.

Relative Humidity Levels in Homes in Canada's North

While excessive moisture and poor air quality is a problem no matter where a home is located, designing and building homes in Canada's North presents unique challenges. The extreme environment and unique social factors that are not present in homes in southern Canada may exacerbate any air quality or moisture problems that develop, as discussed in [Baril et al., 2013]. Preventing these problems from developing in the first place begins with the design of the building envelope.

Baril et al. [2013] examined relative humidity levels of houses in Nunavut, comparing houses with vented and unvented attic spaces. The duplexes, built using single stud, standard wood frame construction, do not have any mechanical ventilation systems. After potential air leakage sites in the building envelopes were identified and sealed, air tightness testing was performed according to Canadian General Standards Board CAN/CGSB-19.10-M86 was performed on the duplexes. The duplexes were found to have an average air exchange rate of $2.0ach$ at $50Pa$ [Baril et al., 2013]. The study found that during most of the monitoring period, the humidity levels in the attic of the Nunavut house (an unventilated cold roof attic) were higher than ambient. As with other work presented on relative humidity levels, the relative humidity levels were monitored but data on the latent gains within the homes was not provided.

Baril et al. [2013] concluded that the Nunavik house built using standard wood frame construction performs well in terms of both thermal performance and air infiltration, but further air tightness improvements could be made. This would reduce heat losses due to infiltration but would increase the need for mechanical ventilation and heat recovery equipment. A number of other studies and incentive programs have been implemented in arctic Canada to improve housing in this region.

The Ventilation Load Index

Regardless of the sensible and latent loads within a conditioned space, HVAC engineers and designers need metrics to assess the influence of the local climate. The Ventilation Load Index (VLI) presented by Harriman III et al. [1997] serves roughly the same purpose for ventilation air as the SHR does for equipment. This index is the "[...] load generated by one cubic foot per minute of fresh air brought in from the weather to space-neutral conditions over the course of one year" [Harriman III et al., 1997]. In the VLI the load is broken up into a dehumidification load and a sensible cooling load. The index is based on local climate information and the desired indoor space conditions.

The VLI is calculated for a given location using data for an entire year. The latent and sensible ton-hours of load per $scfm$ is calculated for each hour of the year and then these values are summed to find the index for the entire year. The VLI allows for direct comparison between locations and is easy for engineers and designers to calculate. The calculation of the sensible and latent loads is also easily modified for different "space-neutral" conditions. As discussed in other works ([Dieckmann, 2008] and [CMHC, 2009]), separating the sensible and latent loads allows the engineer to determine whether or not it would be advantageous to install supplemental dehumidification equipment.

Infiltration through the building envelope is not considered when calculating the VLI. Only fresh air that is brought into the building through an HVAC system is included in the calculations, because the intent of the VLI was to provide a ratio which can be used to select appropriate air conditioning equipment for a given location. The VLI has also been calculated only for dehumidification and sensible cooling load conditions, but results from locations with distinct heating and cooling seasons are also included in the paper. Harriman III et al. [1997] do not explain how heating loads are dealt with. The ventilation indices calculated are also limited to locations in the United States, mostly in southern locations considered to have humid climates. Even the more northerly locations are mostly in humid climates around the Great Lakes (Minnesota, Illinois, Michigan) or along the East Coast (Massachusetts, New York).

Findings from Literature Review

From the works discussed above, it is clear that as building envelope performance increases, the need for supplemental humidity control also increases. From [Lstiburek et al., 2007], the correct sizing and installation of mechanical ventilation equipment is just as important as the type of mechanical ventilation equipment installed. The research highlights from the CMHC focus on improvements to the building envelope, but caution that in older homes, existing HVAC equipment may no longer be appropriate for the house after the renovations have been completed [CMHC, 2012b,a]. In new homes, improving the standard of building envelope construction will likely require additional ventilation equipment, and smaller capacity heating and cooling equipment.

The energy efficiency of housing within Canada and the province of Ontario has improved significantly over the years. Further improvements in both insulation levels and reduced air infiltration are not only possible, but necessary as fuel costs and concern over climate change continue to rise. Improvements in this area are ongoing, and while there is an upper limit to the amount of insulation that can be reasonably added to a home, further improvement to controls and equipment are still possible. Research on the loads required to maintain consistent humidity levels within a house is limited, and the work that has been done is mostly limited to climate zones in the United States.

1.3.4 Examples of High Efficiency Houses in Canada

A green building is a building that has been designed and constructed to have minimal impact on the environment throughout its entire lifecycle, from preliminary design to decommissioning and demolition [EPA, 2014]. The term green building may apply to any building of any size, built for any purpose, but the research presented in this thesis is limited to single family homes.

There are many houses in Canada that have been designed and built with superior energy efficiency in mind, as research or demonstration projects or for consumers. One of the earliest of these projects was the Saskatchewan Conservation House built in Regina, Saskatchewan in 1977. This house was heated using a solar thermal system and was designed to take advantage of as many methods of energy conservation as possible. High levels of insulation, high quality windows, and orientation on the building site were all selected to reduce the space heating loads required in the harsh Regina winters. The house was built as a demonstration project to show the public the energy savings achievable through passive solar design [Besant et al., 1979].

The Drake Landing Solar Community

The Drake landing Solar Community is a planned development of 52 houses in Okotoks, Alberta, built in 2007 [Drake Landing Solar Community, 2013]. The houses are all certified under the R-2000 program and are all connected to a community solar storage system. At the time of writing the system provides 90% of the space heating requirements for the houses in the community [Drake Landing Solar Community, 2013]. Housing in the solar community has proven to be very popular and similar developments are proposed.

The Rainbow PassiveHouse

The Rainbow PassiveHouse duplex in Whistler is one of the first homes in Canada to be certified under the stringent PassiveHouse standard. It was built by Dürfeld Constructors to demonstrate their prefabricated panels and to prove that the PassiveHouse requirements could be met in Canada. The duplex became the first Canadian residential project certified by PassiveHouse in 2012 [BC PassiveHouse, 2012]. Blower door testing showed infiltration rates of $0.25ach$ and $0.3ach$ at 50 Pascals, well below the maximum allowable rate of $0.6ach$ at $50Pa$ under the PassiveHouse standard [BC PassiveHouse, 2012]. A high performance heat recovery ventilator system provides fresh supply air to the home.

The EcoTerra House

The EcoTerra House was built in Eastman, Quebec as one of the houses selected for construction in CMHC's EQuilibrium competition. The competition was announced in 2006 and the EcoTerra proposal was selected for construction in 2007. Since then the house has been constructed, the occupants have moved in, and monitoring data is now available and has been analysed in depth to show the current energy consumption of the house and to find potential areas of improvement [Doiron et al., 2011]. Doiron et al. [2011] go into detail about the design and construction of the EcoTerra House, but also discuss the effect occupant behaviour has on energy consumption for space heating and cooling, and how this changes as the occupants receive feedback on their energy use. Because the house was not built for any particular occupants, they could not be consulted during the design process. Once the occupants had moved in, changes were made that resulted in energy use that exceeded what was predicted during the design phase. The EcoTerra House design team did find that providing real-time, immediate feedback on energy consumption to the occupants did change occupant behaviour, even though the occupants tended to place their own comfort ahead of saving energy. The EcoTerra house is not a net-zero house, and the design team acknowledges that producing a commercially viable design was a higher priority than achieving net-zero, but the monitoring data shows that achieving net-zero or near net-zero would be possible with a few relatively minor changes to the design [Doiron et al., 2011].

The REEP Demonstration House

The Residential Energy Efficiency Project (REEP) house at 20 Mill Street in Kitchener, Ontario, is a renovated century home that has been certified to meet LEED Platinum standards. As a result of the renovations, 86% energy savings were achieved [REEP, 2010]. During the renovations the first priority was to upgrade the entire building envelope, then to upgrade the mechanical and electrical systems within the house. One goal of the retrofit was to maintain the appearance of the home, both on the exterior and the interior. The exterior walls and the basement were insulated using 6 inches of polyurethane for an R-value of R-38, or RSI 6.7. The spray-on foam insulation also minimizes any air leakage through the walls, and also acts as a vapour barrier. Once the insulation was complete a high efficiency boiler was installed to provide hot water for a hydronic heating system and a ground source heat pump was installed to provide both space heating and cooling. An ERV was installed to supply fresh air from outside and control humidity levels within the house. The REEP house shows that it is possible to renovate even an old, poorly constructed (by today's standards) home to not only exceed current building codes, but also to meet or exceed the requirements of most of the green building certification programs available to Canadians.

The green houses presented here represent a small sampling of projects in Canada, from houses built solely as demonstration projects to houses built to be sold to occupants who may or may not have energy efficiency as a priority when looking for a home. All of the projects demonstrate how achievable it is to reduce the space conditioning loads in a house and show the importance of building envelope improvements for significantly reducing these loads. All of the houses presented above, including the homes in Drake Landing, have heat or energy recovery equipment installed to meet air quality requirements.

Chapter 2

Simulation Design

2.1 ESP-r Simulations

In order for a building to meet the increasingly stringent energy efficiency requirements for certification under one of the many green home certification programs, the design and use of the building must be modelled. Building simulation allows engineers and architects to rapidly test different designs and energy efficiency measures, and determine the best combination prior to finalizing the design. Many different computer programs have been developed to perform this modelling, including eQuest, ESP-r, and HOT2000.

DOE-2 is a command-line-based building simulation program developed by James J. Hirsch & Associates and Lawrence Berkeley National Labs in California [Hirsch, 2012]. DOE-2 is a text based building simulation program with a steep learning curve when used without any market interfaces. eQuest is a free building simulation program developed by the Department of Energy in the United States to provide a graphical user interface for DOE-2, eliminating the need to create building input files using a text editor. DOE-2 and eQuest are used primarily for energy cost analyses [Hirsch, 2012]. CanQuest is a release of eQuest specifically for the Canadian market [Natural Resources Canada, 2014a].

ESP-r was developed at the University of Strathclyde in Glasgow, Scotland in the 1970s and is now used all over the world, primarily for research [McQuiston et al., 2005]. It is an open source program that allows the user to use either a graphical interface or to create input text files to build the model. Because it is open source, ESP-r has been under continuous development since it was first released, and its wide range of simulation capabilities is constantly evolving and expanding.

HOT2000 was developed by Natural Resources Canada (NRCan) to provide a simulation tool for those working on green home design in Canada, including energy cost data. HOT2000 uses ESP-r as its back-end code, but provides a user interface that requires less-specialized knowledge. Average values built into HOT2000 come from data collected by NRCan, providing real values for Canadian housing stock. An updated program, HOT3000, is in development and will eventually replace HOT2000 [Natural Resources Canada, 2013].

While both CanQuest and HOT2000 are well-established building simulation programs, they were not considered for this research because it was unclear whether they would provide latent load results and other hygrothermal performance data. Instead, ESP-r was chosen as it is an open-source software that was developed for use in research. Its continuous use in research since it was released means that as a program, new features for ESP-r are constantly being developed and put into use. This makes ESP-r a powerful yet flexible program. ESP-r is capable of outputting a varied range of data, allowing users to select the desired outputs based on their needs. Not all available building simulation programs output all of the data that is available through ESP-r, and not all of them output the data that is required for the analysis required for this study. In addition, the capabilities of ESP-r are very good, and provide many options for simulations that may not be possible in other programs. For example, ESP-r has shading and glazing options, as well as shading control options, not available in other programs.

Using ESP-r also allows for continuation of this work to examine other aspects of hygrothermal performance that will not be explicitly considered during this project, such as the formation of condensation on interior surfaces or within the envelope assemblies.

2.1.1 General Procedure for Simulations

The design and specification of the house is modelled using the methods described in the ESP-r resources available such as [Hand, 2010]. The walls, roof, and other features for each case were added to the appropriate construction databases in ESP-r. The windows were specified using the software GSLEdit and the complex fenestration construction (CFC) method developed by [Lomanowski, 2008].

The geometry of the houses simulated in this study were based on a house used in a study presented in [Building Science Corporation, 2006]. In the BSC study, the three bedroom, one and a half storey house was located in Juneau, Alaska. The Juneau house was designed to be energy efficient, with high levels of insulation, excellent windows, and a heat recovery ventilator (HRV). For the ESP-r simulations used in this study, the dimensions of the Juneau house were converted to metric units and then rounded to the nearest meter for convenience. Exterior finishes were selected from the standard materials available in the ESP-r materials databases. The same geometry and exterior finishes were used for all of the simulations is this study.

Once the geometry was input and construction materials were selected, the equipment was added to the simulations. Occupancy and casual gain schedules were developed and infiltration through the envelope was input based on blower door test data.

The Juneau House

Figure 2.1: Image of Juneau house [Building Science Corporation, 2006]

The Juneau house designed by Building Science Corporation for Building America is one and a half storeys, with approximately 1190 square feet (110 m^2) of floor area based on exterior dimensions. The house has three bedrooms and is intended as a single family dwelling. A basement is not included in the design, and instead the house is elevated on piers due to soil conditions in Alaska. Excavations are not always practical where permafrost or rocky terrain is present.

The total wall area of the Juneau house is 1660 ft^2 (154.2 m^2). The house is designed with two doors that are included in the total wall area. The house as designed has 11 windows, with a total area of 180 ft^2 (16.72 m^2), which represents about 11% of the total wall area of the house.

The roof of the Juneau house has a two foot wide overhang on all sides. The total slope area of the roof is 1368 ft^2 (127.1 m^2), including the 280 ft^2 (26.0 m^2) that make up the overhang. The calculated value of the roof area does not include the roof over the front porch.

The Juneau house is designed with a radiant heating system and a separate ventilation system. Because of the cool climate in Juneau, a cooling system is not necessary. Heat recovery equipment was installed on the ventilation system to reduce the amount of energy required for space heating. Exhaust fans were installed in the bathroom and kitchen to meet indoor air quality standards.

The Toronto House

The Toronto house is similar to the Juneau house, but some changes have been made. First, all dimensions for the Juneau house were given in Imperial measurements, but ESP-r operates solely in metric. Dimensions from the plans for the Juneau house were converted to metric units and then rounded off for convenience. The roof overhang and the front porch were not modelled in ESP-r and the number of bedrooms was reduced to two. Figure 2.2 shows a sketch of the house design that was used for all simulation runs.

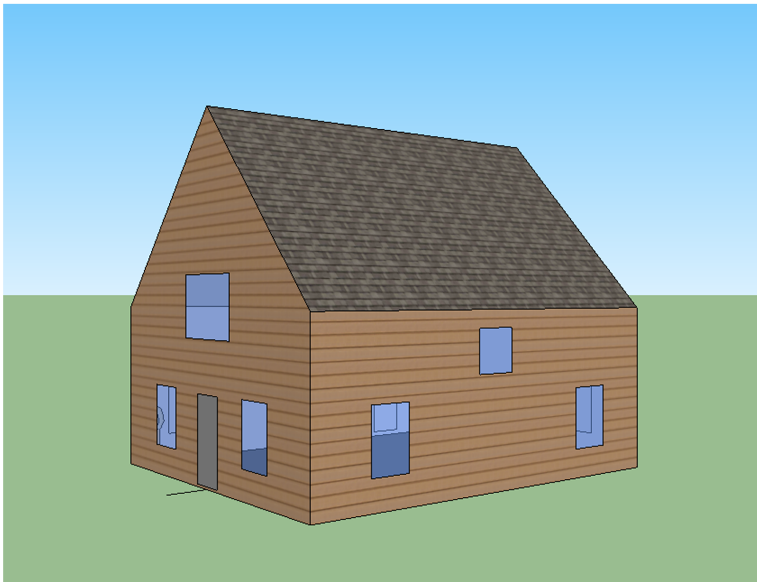


Figure 2.2: Sketch of Toronto house as seen from south-west corner

Several versions of the same house were constructed. The construction assemblies for each of the houses simulated were designed to meet building codes of one of three different eras - approximately 1970, 2006, and a final construction that is extremely energy efficient. Each construction assembly was added to the construction database in ESP-r, and each house was assigned the appropriate assemblies for that era.

The first house was designed to meet the building codes and infiltration levels from the 1970s. This house provides a baseline to which the other houses will be compared. Mechanical ventilation was not used for this house. This house will be called the 1970's house.

The second house was built to meet the minimum standards set out in the 2006 Ontario Building Code. At the time of writing, this is the current building code in effect for residential construction in Ontario. This house will be called the 2006 house or the Building Code house. In addition to the increased insulation and better windows, compared to the 1970s house, an HRV was added to maintain air quality within the house. Infiltration levels were adjusted to match levels consistent with housing stock that was built to meet the 2006 Ontario Building Code.

The third house was built to be exceptionally energy efficient, exceeding all of the requirements for the 2006 OBC. The levels of insulation are double those of the 2006 house for all assemblies, the windows are the best available, and an HRV was once again included. Infiltration levels are very low for this house, consistent with construction where care has been taken to seal all openings. This house construction has been named the Super House, and it is this simulation that was examined most closely to see how different factors such as occupancy and shading controls affect the equipment loads. Different letters will be used to designate the different simulations run using this construction.

For the purposes of this study the heating and cooling equipment installed in the houses were not explicitly defined and the simulations all used ESP-r's idealized plant option. The loads that the equipment must meet are of interest in this study, but the type of equipment is not of immediate concern. Large maximum capacities were specified for the heating, cooling, humidification, and dehumidification equipment since the range of loads expected for each house were unknown. Setting the capacities to exceed any loads that the house will experience eliminates the possibility of the equipment being unable to meet the demands of the space.

Once the geometry and assemblies of the house were specified and the HVAC equipment was set up, occupancy and casual gain schedules were created. These schedules were compiled based on research presented in [Swan, 2010], [Pietila, 2011], and [Geving and Holme, 2011]. No single source had all the information needed to create occupancy schedules for both sensible and latent loads.

2.2 Geometry and Construction Assemblies

2.2.1 Wall Assemblies

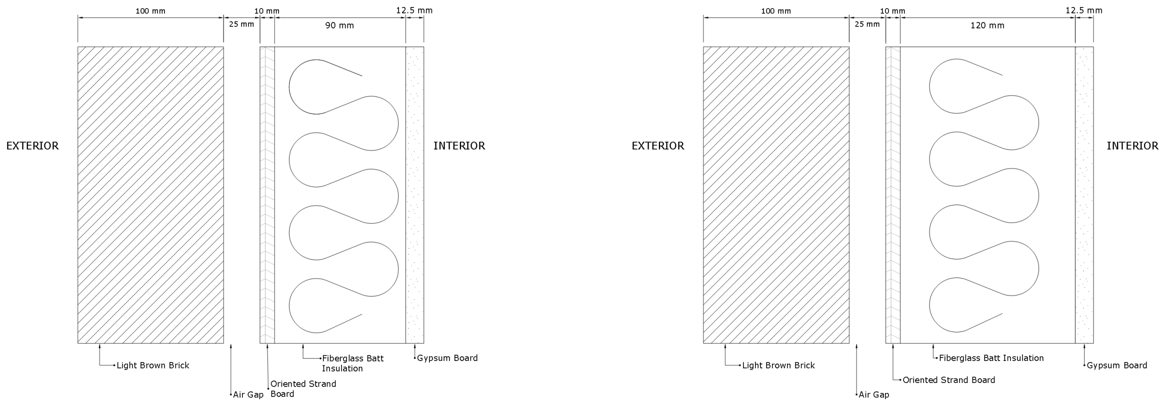
Walls for all houses were specified assuming typical multi-layered construction for each case. Thermal bridging across the walls from fixtures or hardware was not explicitly considered. The 1970 house and 2006 house both use fibreglass batt insulation, and the Super House uses extruded polystyrene (EPS) insulation. All of the materials used in the assemblies were standard materials available in the ESP-r materials database.

The wall assemblies were constructed based on the perfect wall presented in [Lstiburek, 2010]. In this paper, the air and vapour barrier is located between the thermal insulation and the wood structure of the house, i.e. on the indoor side of the insulation. The ESP-r materials database does not include any materials that can be used explicitly as air or vapour barriers. However, these materials are typically thin sheets that do not provide any additional insulation in the building envelope, and can be left out of the wall assembly thermal models. Air barriers will affect the infiltration rates for the house, which will be reflected in the AIM-2 input file. This will be discussed in Section 2.4.3.

Table 2.1 shows the R-values used for each wall assembly, and Figure 2.3 shows the construction of each assembly.

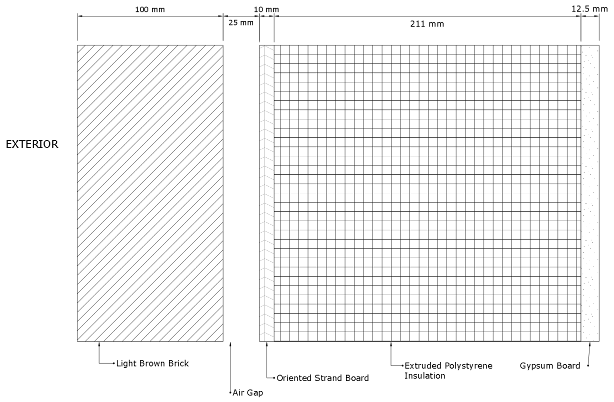
Table 2.1: RSI values for insulation in walls of each house model

House	**1970's House**	**2006 House**	**Super House**
R-Value, $\left(\frac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	12	19	40
RSI, $\left(\frac{m^2K}{W}\right)$	2.11	3.34	7.04
Insulation Material	Fiberglass batt	Fiberglass batt	EPS
Material Thickness, mm	90	120	211
Conductivity, $\left(\frac{W}{m * K}\right)$	0.036	0.036	0.030



(a) 1970 house

(b) 2006 house



(c) Super house

Figure 2.3: Construction of each wall assembly

2.2.2 Roof Assemblies

For all houses simulated, the roof is a vaulted cathedral ceiling with no attic space as shown in Figure 2.4. The roof assemblies were built up in the same way the walls were, using a multi-layered construction. As with the walls, thermal bridging within the roof assembly was not explicitly considered.

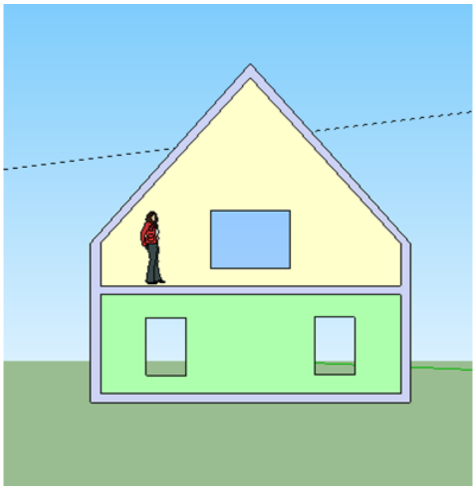
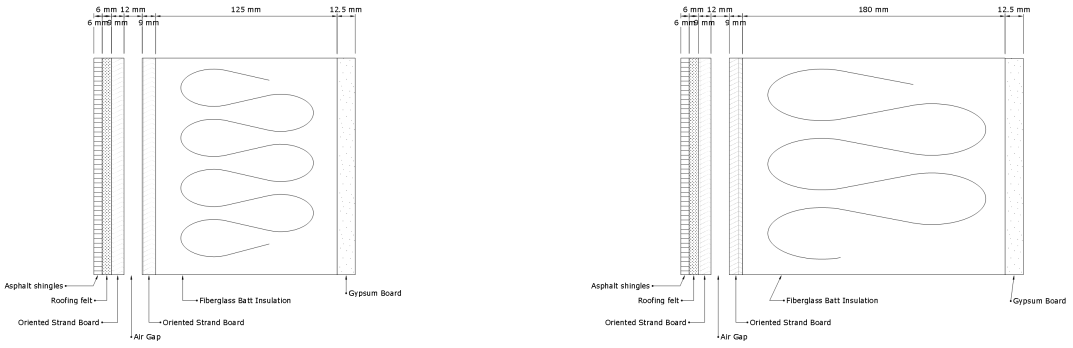


Figure 2.4: Cutaway section of Toronto house showing vaulted ceiling

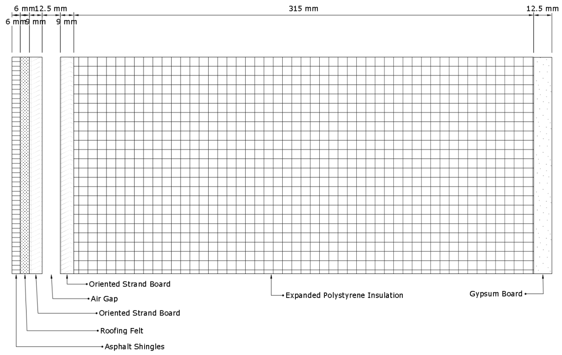
Table 2.2 shows the R-values of the insulation used for each roof assembly, and Figure 2.5 shows the construction of each assembly.

Table 2.2: Insulation levels for roof of each house

House	**1970‘s House**	**2006 House**	**Super House**
R-Value, $\left(\dfrac{ft^2 * °\text{F} * hr}{BTU}\right)$	20	30	60
RSI, $\left(\dfrac{m^2K}{W}\right)$	3.47	4.93	10.57
Insulation Material	Fiberglass batt	Fiberglass batt	Expanded polystyrene
Material Thickness, mm	125	180	315
Conductivity, $\left(\dfrac{W}{m * K}\right)$	0.036	0.036	0.030



(a) 1970 house (b) 2006 house



(c) Super house

Figure 2.5: Construction of each roof assembly

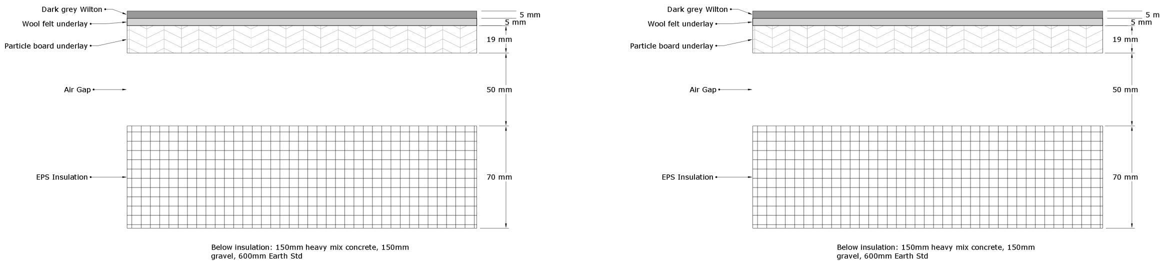
2.2.3 Floor Slab Assemblies

The floor of the house used in all simulations was a concrete slab on grade construction. A basement was not included in the model. The slab on grade floor uses a standard ground temperature profile to calculate the heat transfer between the floor slab and the ground. No standard temperature profiles are available in ESP-r for North America, so one of the included profiles from a location with a similar climate to Toronto was used instead. The standard ground profile for all simulations located in Toronto, Ontario, was the standard ground profile for Berlin, Germany, at a depth of 0.5 meters.

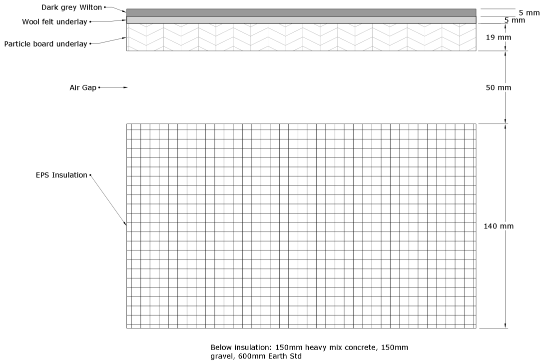
The construction details of the floor slabs for each house are shown in Table 2.3, and sketches of each assembly are shown in Figure 2.6. The floor construction for the 1970 house and the 2006 house are identical.

Table 2.3: Assembly and insulation levels for floor of each house

Construction Layer	**Material**	**Conductivity** $\left(\frac{w}{m*K}\right)$	**Thickness 1970's House (mm)**	**Thickness 2006 House (mm)**	**Thickness Super House (mm)**
1	Earth Std	1.28	600	600	600
2	Gravel based	0.52	150	150	150
3	Heavy mix concrete	1.4	150	150	150
4	EPS 80 mm	0.04	70	70	140
5	Air gap	0.0	50	50	50
6	Particle board underlay	0.11	19	19	19
7	Wool felt underlay	0.04	5	5	5
8	Dark grey Wilton	0.06	5	5	5



(a) 1970 house (b) 2006 house



(c) Super house

Figure 2.6: Construction of each floor slab assembly

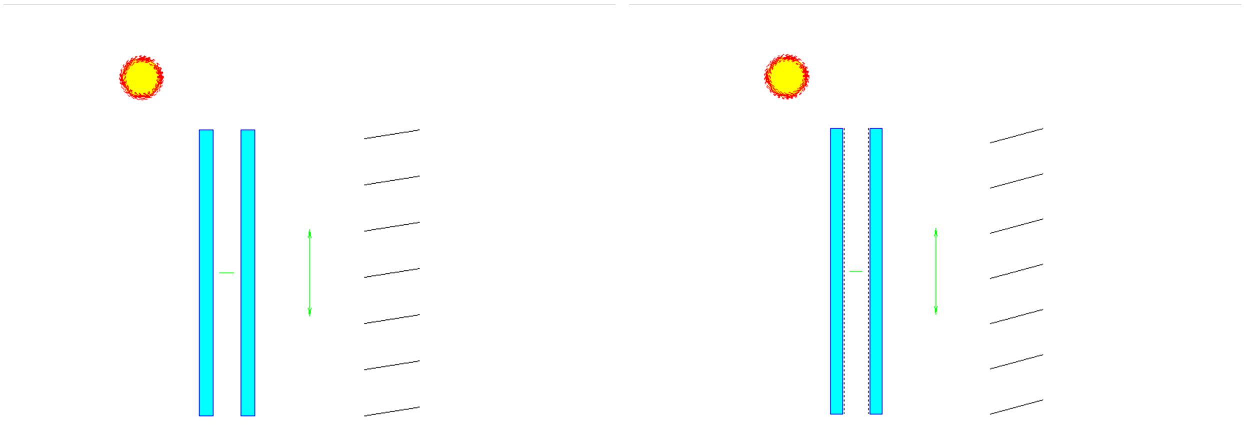
2.2.4 Window Assemblies

Windows were added to the ESP-r model using GSLEdit, a glazing and shading layer editor, and simulations used the method of modelling complex fenestration constructions (CFCs) developed by Bart Lomanowski at the University of Waterloo [Lomanowski, 2008]. Using this method, window assemblies are constructed in GSLEdit using the glazing libraries within that program, and then transferred to ESP-r to create the .cfc file. This method allows for different glass panes including those with low-emissivity (low-e) coatings, different fill gasses, and shading options to be added to the ESP-r model. Using GSLEdit also allows dynamic shading controls to be implemented. The window assembly information is compiled in Table 2.4, and screenshots of the different windows from GSLEdit are shown in Figure 2.7. The air gap between the interior pane of glass and the blinds is vented indoors for the 1970 and the 2006 glazings. For the Super glazing this gap is set to "normal" within GSLEdit.

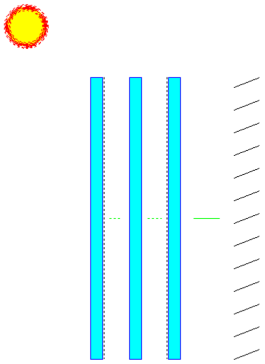
For the 2006 glazing, low-emissivity coatings are located on two surfaces. For double paned windows, a single low-e coating is more typical.

Table 2.4: Window constructions used for each house

Window Property	**1970's House**	**2006 House**	**Super House**
Number of Panes	2	2	3
Glass Used	15PVB6.DUP	LOWE_6.LOF	LOWE_6.LOF for external panes, CLEAR6.LOF for internal pane
Coatings	None	Surfaces 2 and 3	Surfaces 2 and 5
Coating Emissivity	N/A	0.157	0.157
Fill Gas	100% air	100% air	10% air, 90% argon
Solar Heat Gain Coefficient	0.699	0.598	0.527



(a) 1970 house (b) 2006 house



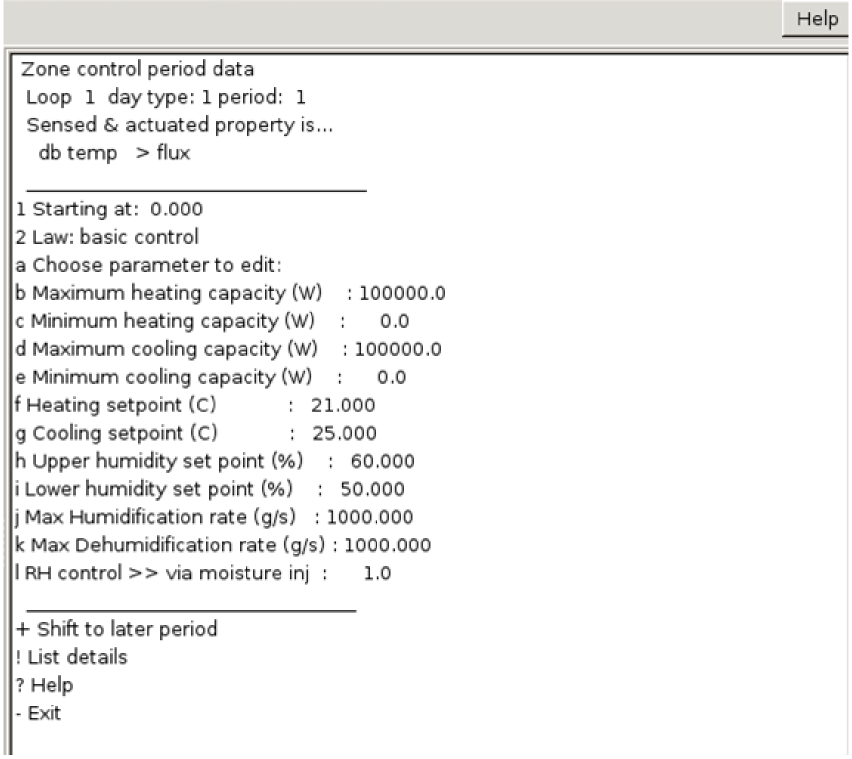
(c) Super house

Figure 2.7: GSLEdit constructions of window assemblies

2.3 Controls and the Heat Recovery Ventilator

The following section describes the control rules used to maintain the setpoints selected for the houses. As described in Section 2.1.1 earlier, the control loops were set up with the maximum capacity available within the program since the actual peak loads were unknown.

The temperature and relative humidity within the house were controlled using a basic controller for cooling and heating. If no temperature setback is desired, there is only one control period throughout each day of the simulation, and the same conditions are in effect throughout the entire year.



```
 Zone control period data
  Loop  1  day type: 1 period:  1
  Sensed & actuated property is...
    db temp   > flux
  ________________________________
1 Starting at:  0.000
2 Law: basic control
a Choose parameter to edit:
b Maximum heating capacity (W)    : 100000.0
c Minimum heating capacity (W)    :      0.0
d Maximum cooling capacity (W)    : 100000.0
e Minimum cooling capacity (W)    :      0.0
f Heating setpoint (C)            :   21.000
g Cooling setpoint (C)            :   25.000
h Upper humidity set point (%)    :   60.000
i Lower humidity set point (%)    :   50.000
j Max Humidification rate (g/s)   : 1000.000
k Max Dehumidification rate (g/s) : 1000.000
l RH control >> via moisture inj  :      1.0
  ________________________________
+ Shift to later period
! List details
? Help
- Exit
```

Figure 2.8: Screen shot of the control loop inputs for the house

Figure 2.8 shows the control loop inputs for the controls for the houses in Toronto. The basic control law will add or extract heat and moisture to maintain the desired temperature and relative humidity.

2.3.1 Setpoints

The same setpoints were used for the first five simulation runs of this study, and the final simulation run was set up with a single setpoint for both heating and cooling. The setpoints were chosen based on the standards for thermal comfort set out in ASHRAE Standards 55 and 62.2 and Chapter 9 of the 2009 ASHRAE Handbook of Fundamentals.

Comfort standards for temperature and relative humidity are defined by ASHRAE Standard 55. This standard recommends dry bulb temperature ranges for summer and winter, as well as upper humidity ratio limits [ASHRAE, 2009a]. No lower humidity limits are provided but studies cited by ASHRAE show that lower humidity will lead to occupant discomfort [ASHRAE, 2009a]. The temperature and humidity limits given in the 2009 ASHRAE Fundamentals Handbook do not apply perfectly to residential applications, as most thermal comfort studies are performed using office buildings. In these studies the occupants are assumed to dress a certain way and perform specific tasks. Even under these circumstances, not every one of the building's occupants will be satisfied with the indoor conditions. In residential buildings occupant behaviour and comfort are much less rigidly defined. Since the occupants of a house or apartment unit have more control over the heating and cooling within their home the setpoints may vary considerably from one house to another.

For the simulations in Toronto the heating setpoint was 21 °C and the cooling setpoint was 25 °C. These setpoints represent the dry bulb temperature within the house. The control system will activate either the heating or cooling function of the HVAC equipment.

Relative humidity within a conditioned space, especially in houses which are typically built using wood frames, must be controlled to prevent condensation and mould growth, in addition to providing a comfortable environment. The occurrence of condensation on walls or other surfaces will not be examined within this study. The upper relative humidity limit was set to 60% RH. A relative humidity higher than this could result in thermal comfort problems and mould growth if other conditions are favourable [ASHRAE, 2009a].

The lower relative humidity limit was set to 50% RH. By code, vapour barriers must allow the interior space to be maintained at 35% RH during the winter [OBC, 2006]. The relative humidity limits specified here are narrow, but could easily be changed to allow a wider range of conditions. While these setpoints may not be appropriate for all the houses simulated, using the same setpoints for all of the houses makes comparisons between simulations straightforward. However, the impact of having such a high lower limit for the relative humidity must be considered when examining the results of the simulations.

ESP-r controls humidity by specifying the relative humidity, not the humidity ratio. The relationship between the relative humidity and the humidity ratio (ω) is given by Equation 2.1. The dry bulb temperature of the air will affect the relative humidity. The higher the dry bulb temperature, the more moisture the air will be able to hold.

Since there is a difference between heating and cooling setpoints, the temperature will be allowed to free float if it is between the two setpoints. The humidity control will do the same between the upper and lower relative humidity limits.

$$RH = \frac{\omega * P_{atm}}{0.6219 P_{sat}} \tag{2.1}$$

Once the simulations with the range of allowable temperatures and relative humidities were complete, a final simulation was run using the super insulated house with a new control file. This new control file was set up to maintain a constant temperature and RH at all times. The results from this simulation will be compared to the results from the simulations that have a range of acceptable temperatures and humidity levels.

Modelling the HRV

As discussed previously, the component details of the HVAC systems need not be explicitly defined. Only the equipment loads are of interest. However, the HRV must be modelled explicitly to account for the moisture that accompanies the outside air. HRVs only provide sensible heat transfer between the supply and exhaust air streams. To correctly model the HRV, the air that goes through the HRV and into the house will have the same humidity ratio as the outdoor air, but not the same relative humidity. If the HVAC equipment in the house is added to the ESP-r model using an explicitly defined plant model, the HRV could be added to the model using built in plant components. Since this was not the case for the Toronto houses and the built-in plant components could not be used so another method for modelling the HRV was found. A component diagram showing heat flows into and out of the house is shown in Figure 2.9 below.

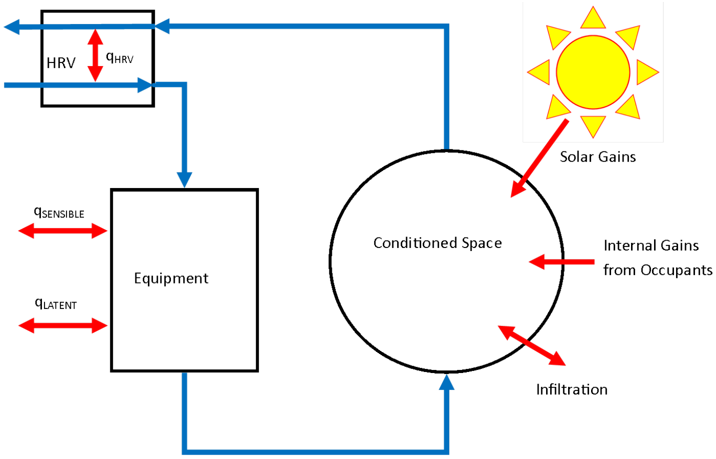


Figure 2.9: Component diagram of the HRV showing heat flows

The most straightforward way to add the HRV to the model was to set up two dummy zones outside the house as shown in Figure 2.10 [Strachan, 2013]. One dummy zone represents the supply side of the HRV, and the other dummy zone represents the exhaust side.

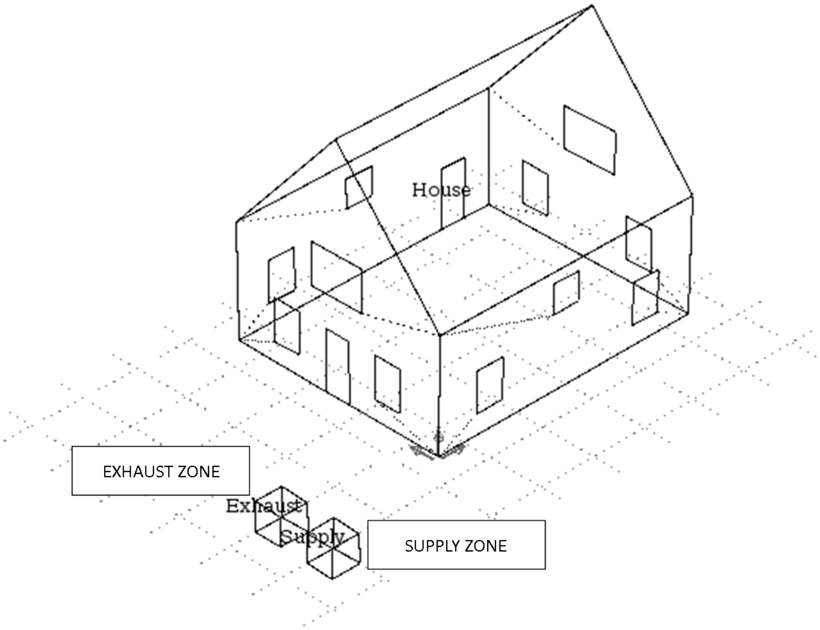


Figure 2.10: Screen shot of ESP-r model showing dummy zones

Control of the dummy zones is set up to reflect the conditions of the house zone as well as the outdoor conditions. The HRV control loop is set up to control the temperature of the supply zone based on the temperature of the exhaust zone. The dummy zones are specified as adiabatic on all sides so that they are not affected by the outdoor conditions or by insolation.

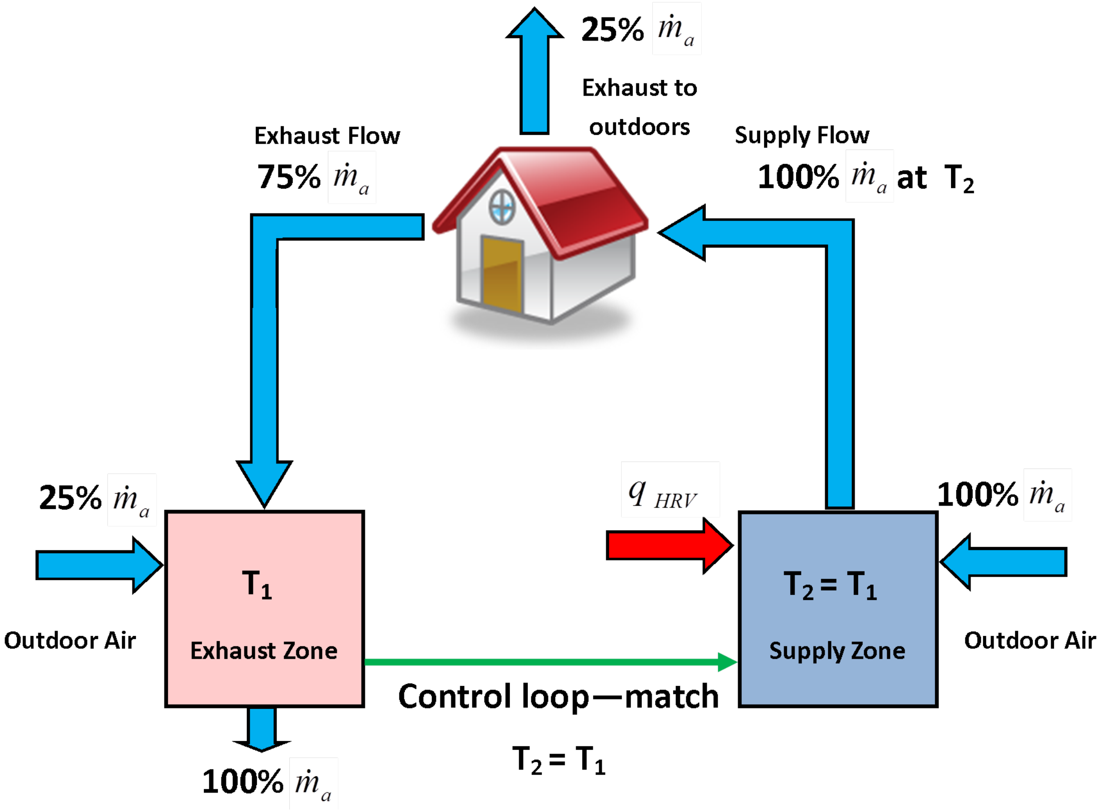


Figure 2.11: HRV control loop

Figure 2.11 shows the control loop for the HRV, and the air flows between the two dummy zones and the house zone. The temperature of the supply zone must equal the temperature of the exhaust zone. The temperature of the exhaust zone is determined by the temperature of the air coming from the house, and the amount of outside air that is mixed with the house air, set by the effectiveness of the HRV. For this study an effectiveness of 75% was selected for the HRV.

The HRV control law is “Match sensed and recorded values (ideal)”, and this control loop operates continuously throughout the simulations. This control law senses the temperature in the exhaust zone and provides either sensible heating or cooling to the supply zone until the supply flow to the house is at the same temperature as the exhaust zone. Only sensible conditioning is provided to the supply zone.

The supply zone provides $38L/s$ of air to the house as per ASHRAE Standard 62.2. The exhaust zone receives $38L/s$ of air, but only 75% of this $38L/s$ comes from the house zone. The remaining $9.5L/s$ comes into the supply zone from the outdoor environment. This accounts for the 75% effectiveness of the HRV. The control loop then heats or cools the air in the supply zone to the temperature of the exhaust zone before supplying air to the house.

For the HRV model, the sensible loads required for conditioning the supply zone are not included in the loads that will be analysed as presented in Chapter 3.

2.4 Occupancy and Casual Gain Schedules

The occupancy and casual gain schedules take into account both sensible and latent heat gains within the space. There is a great deal of previous work investigating the sensible gains from appliances, but no typical or design values were found on moisture generation rates in any type of building, residential or otherwise. The occupancy schedule is input into ESP-r with all the sensible and latent gains from the occupants of the house depending on their activity level, and the casual gain schedule contains all the gains due to appliances and other items within the house.

2.4.1 Occupancy Schedule

When creating the occupancy schedule, two adult occupants were assumed to be living in the house. It was also assumed that both occupants work outside the home and that neither of the occupants is in the house between the hours of 8:00am and 5:00pm, Monday through Friday. A person will constantly generate sensible and latent heat through their metabolism, and when a house is occupied this heat and moisture affects the conditions within the house. These rates are extensively detailed in Chapter 9 of the ASHRAE Handbook of Fundamentals [ASHRAE, 2009a], and will depend on a person's activity level, clothing, general health, and various other factors. The rates used in the development of the CHREM database, which were used for the occupancy schedules in this study, are shown in Table 2.5 [Swan, 2010]. Women are assumed to generate heat and moisture at 85% of the rate generated by adult males. It was assumed that there is one male occupant and one female occupant in the Toronto house.

Table 2.5: Occupant sensible heat and moisture generation rates [Swan, 2010]

	Male (W)	**Female (W)**
Sensible heat generation, awake	81.9	69.62
Moisture generation, awake	48.1	40.89
Sensible heat generation, sleeping	72.45	61.58
Moisture generation, sleeping	42.55	36.17

Using the rates presented in Table 2.5, the occupancy schedule for weekdays is shown in Table 2.6 and the occupancy schedule for weekends and holidays is shown in Table 2.7. It is assumed that both occupants will be in the house during the day on weekends and holidays. Overnight when the occupants are sleeping the moisture and heat generation rates for the occupants are reduced to 75% of their nominal values.

Table 2.6: Occupancy schedule, weekdays, for two adults living in house

Period start time	**Time of Day**	**Sensible Gain (W)**	**Latent Gain (W)**
00:00	Night	134	79
05:00	Morning	152	89
08:00	Daytime	0	0
17:00	Evening	152	89
21:00	Night	134	79

Table 2.7: Occupancy schedules, weekends and holidays

	Saturday		**Sunday**		**Holidays**	
Period start time	Sensible	Latent	Sensible	Latent	Sensible	Latent
00:00	134	79	134	79	134	79
08:00	152	89	152	89	152	89
21:00	134	79	134	79	134	79

The sensible and latent gains listed in Tables 2.6 and 2.7 do not include any sensible and latent gains from cooking, bathing, or other activities or equipment within the house. These gains will be described in Section 2.4.2. Complete input files for the occupancy schedules are found in Appendix A.

2.4.2 Casual Gain Schedules

Showers, cooking, washing machines and dryers, dishwashers, lights, and other appliances all contribute to the casual gains within the conditioned space. Some will add sensible heat to the space, some will add moisture the the air in the space, and other will contribute both sensible and latent heat. For example, computer equipment will add sensible heat to a room, house plants will add a small amount of moisture, and cooking will add both sensible heat and moisture to the conditioned space.

The sensible gain from an appliance that does not give off moisture is equal to the electrical power that the appliance draws. Data on the electrical draws from various types of appliances is available in [Pietila, 2011] and [Swan, 2010]. Geving and Holme [2011] did not provide values for the ESP-r inputs, but their data was used to confirm that the peaks shown in Figure 2.12 were appropriately placed.

ESP-r provides four fields for casual gain labels, one of which is already taken up with Occupancy. The remaining labels were chosen to be Showers, Lighting, and Other. Showers and Lighting are straightforward, while Other includes small power, the stove, dishwasher, other kitchen appliances, and anything else that needs to be considered to complete the casual gain schedule.

Lighting was created as a separate label since the lighting in a house will only contribute to sensible loads, and the lighting use may not correspond well to the use of other appliances in the house. The sensible gains that lighting adds to the house are small, consistent with a house that has had energy efficient lighting installed and whose occupants take advantage of daylighting when possible.

Showering can put a large amount of moisture into the air in a house in a short period, so it was given its own label in the ESP-r casual gain schedule. Two shower periods were defined, one in the morning between 06:00 and 07:00 and one in the evening between 21:00 and 22:00.

The final label was Other. This label includes appliances such as tea kettles, a stove, dishwasher, washing machine and dryer, and any other appliances or devices that add sensible gains, latent gains, or both to the space. Small power and power draws from electronics that are left plugged in are also included under this label. While using a washing machine and dryer would be included under this label, these appliances were not included in the casual gain schedule for this house.

When all the internal gains have been specified, two large spikes in the internal gains within the house are seen (Figure 2.12). One is in the morning when the occupants are getting ready for the day, and a second spike is in the evening when the occupants are cooking dinner.

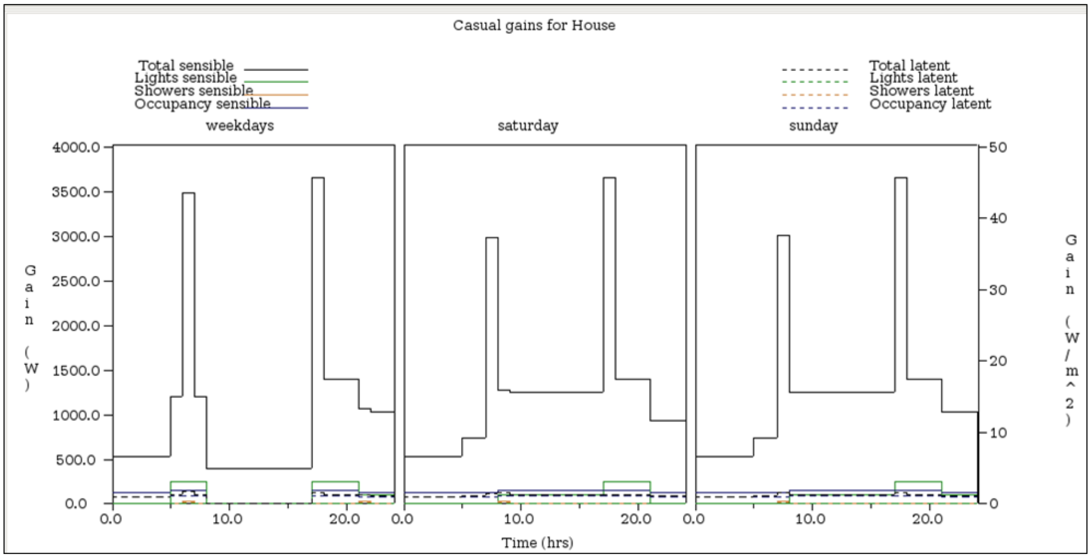


Figure 2.12: Occupancy and casual gain schedules for two occupants for weekdays, Saturdays, and Sundays. Holidays are the same as Sundays.

Complete input files for the casual gain schedules are found in Appendix A. The schedule developed here is intended to match the peaks and valleys of internal gain in the house as a result of common activities and appliances as seen in Figure 2.12.

2.4.3 Infiltration Rates

There are two methods of adding infiltration to an ESP-r model. The first method is to set up an air flow network connecting the different zones and the outdoor environment. This method is described in detail in Chapter 11 of the ESP-r Cookbook [Hand, 2010]. In an air flow network, nodes are placed at different points in the model and any air-flows between nodes are entered. This method requires advanced knowledge of air flow rates between rooms and through doors, windows, and other building features.

The second method of incorporating infiltration in the model is the AIM-2 model, which is built into ESP-r. The AIM-2 model was developed by Walker and Wilson at the University of Alberta in 1990 and applies only to low rise, single family homes. The AIM-2 model allows for the infiltration through the envelope into a home to be defined using blower door test data. Blower door tests performed according to CAN/CGSB-149.10.M86 are the standard method of determining air infiltration rates and will give an air change rate at $50Pa$ and an Estimated Leakage Area (ELA) in square centimetres.

Blower door test results for the 1970 house and the 2006 house were taken from the average values collected by NRCan and built into HOT2000. An infiltration rate for the Super House was selected based on houses that were designed to be extremely energy efficient, such as the Saskatchewan Conservation House, with an air exchange rate of $0.6ach$ when tested [Besant et al., 1979], the EcoTerra House, with an air exchange rate of $0.85ach$ [Doiron et al., 2011], and the Factor 9 House in Regina with an air exchange goal of $0.5ach$ [CMHC, 2007]. All of these air exchange rates are at $50Pa$. Most green home certification standards also have maximum allowable levels of infiltration from a blower door test, and this was considered when selecting the rate for the Super house.

While the PassiveHouse standard and houses built by the CMHC and other organizations show that infiltration rates of $0.6ach$ or less are achievable, an air infiltration rate of $0.8ach$ was selected for the Super House. The infiltration rates and ELAs for each house are compiled in Table 2.8.

Table 2.8: Infiltration rates and estimated leakage areas for houses

House	**1970's House**	**2006 House**	**Super House**
ACH at $50Pa$	6.68	3.04	0.8
ELA (cm^2)	616.10	287.30	50

In addition to the blower door test data, the AIM-2 file also requires inputs describing the house and its surroundings. The AIM-2 file uses these inputs to calculate the load on the house from air infiltration at each timestep. Infiltration depends on factors such as the outdoor temperature, wind speed and direction, terrain near the house, and any surrounding buildings. The terrain around the Toronto house was assumed to be flat and grassy and there are no other buildings located immediately adjacent to the house. The terrain around the weather station is also assumed to be open and flat.

Shielding refers to any obstruction that could affect the air flow patterns around the house, and in turn affect the infiltration through the building envelope [AIM2, 2010]. For this study, there is no shielding on the walls of the house and no local shielding on the flues or other air intakes. The diameter of all flues, including domestic hot water flues, is assumed to be zero, consistent with a house that is heated with electric baseboard heaters or sealed combustion equipment. The AIM-2 input files for each house are included in Appendix A.

2.5 Variations on the Super House

To examine other factors that may affect equipment loads, three variations on the Super House have been simulated. The factors chosen for examination are increased occupancy (Super House B), dynamic shading control (Super House C), and a single setpoint instead of a range of set points (Super House D). The rosettes for these variations will be compared to those for the base case of the Super House (Super House A) to see which of these factors affect the equipment loads, and how.

In addition to the different variations on the house in Toronto, simulations using the construction and operational inputs for Super House A were run in different locations across Canada. The rosettes for these locations were produced and compared to the rosette for the house in Toronto. For these simulations there were no changes to the models other than the location and climate files.

2.5.1 Occupancy and Casual Gain Schedules

The first variation, Super House B, will increase the occupancy within the house from two residents to four, and the schedule was updated so that two occupants are home during the day on weekdays.

Adult heat and moisture generation rates were used for all four occupants. Rates for two men and two women living in the house were used. On weekdays there was one male and one female in the house during the day and the other two people leave the house. The new occupancy schedules for weekdays, weekends, and holidays are shown in Figure 2.9, and are created using the same heat and moisture generation rates detailed in Section 2.4.1. Occupancy schedules for weekends and holidays are included in Appendix A.

Table 2.9: Occupancy schedule, weekdays, for four adults living in house

Period start time	**Time of Day**	**Sensible Gain** (W)	**Latent Gain** (W)
00:00	Night	268	157
05:00	Morning	303	178
08:00	Daytime	152	89
17:00	Evening	303	178
21:00	Night	268	157

Creating the original casual gains schedule for two occupants required a number of estimations and assumptions which also apply to the schedule with four people. There are also some entries that do not change if the occupancy changes.

When updating the casual gain schedules to reflect the increased number of occupants, three different appliances and activities were adjusted. Showers, running the dishwasher, and cooking were examined, and the sensible and latent gains for these activities were increased to reflect the increase in occupancy. The lighting and small power gains were also adjusted to reflect the increased number of occupants in the house. Since there are now occupants in the house between 08:00 and 17:00 on weekdays, there will be lights on and additional small power gains during the day.

Figure 2.13 shows the updated casual gain and occupancy schedules in ESP-r for Super House B. Complete files for the occupancy and casual gains schedules are included in Appendix A.

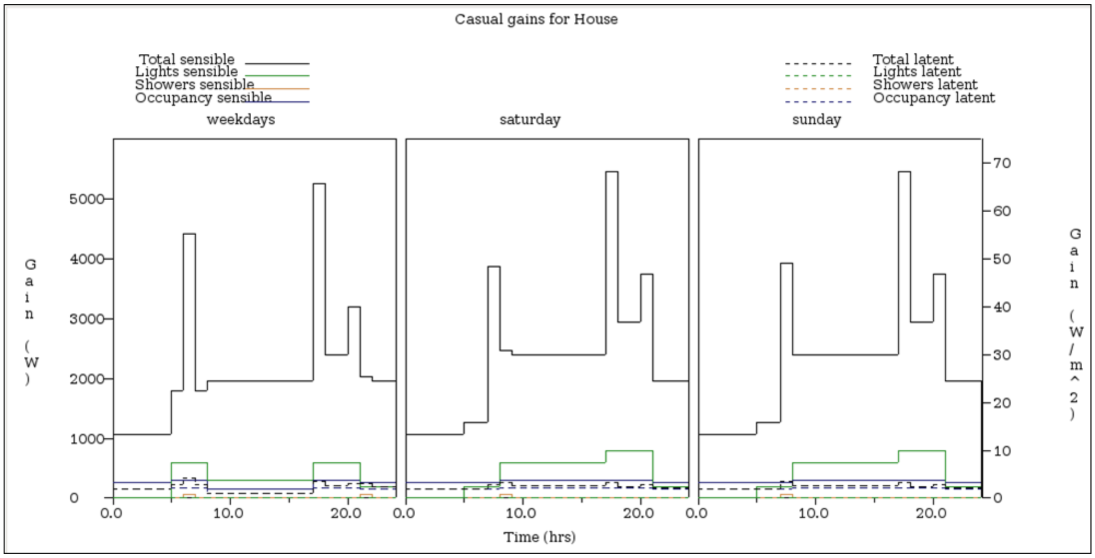


Figure 2.13: Occupancy and casual gain schedules for Super House B for weekdays, Saturdays, and Sundays. Holidays are the same as Sundays.

2.5.2 Static versus Dynamic Shading Control

The 1970's house, the 2006 house, and Super House A all use static shading. The shades on these simulation runs are light coloured Venetian blinds that have a slat angle of 22.5 ° from horizontal, down toward the outdoor side, to allow some light and solar heat gain to enter the house. This slat angle does not change at any point during these simulations.

The main purposes of shading are to control glare and to improve thermal comfort by controlling the solar heat gain within a space [Lomanowski, 2008]. In the winter, closing blinds in the evening and then opening them again in the morning could potentially reduce heat loss through the windows overnight, reducing equipment loads. In the summer the blinds could be left open overnight to take advantage of cooler outdoor temperatures, and then closed during the day to prevent overheating of the conditioned space. A constant slat angle for the blinds assumes that the occupants do not change the angle of the blinds for the entire year being simulated. This is not necessarily realistic, since even someone who does not care about energy efficiency will probably make the effort to adjust their blinds once the slat position begins affecting their comfort, either by making the space too warm or if glare begins affecting their activities.

In southern climates, the blinds are likely to be closed at night because the occupants want privacy within their home, but in more northern locations closing the blinds may be done to provide occupants with a dark enough environment to sleep well during the summer.

For the simulation of Super House C the blinds are opened or closed based on the level of insolation that the window is receiving. The state of the control loops used to activate the blinds can be examined using the XML output feature in ESP-r.

To set up the shading control so that the windows facing each direction can be controlled independently, four CFC types are assigned to the house. All four CFC types use the same GSLEdit file but each type corresponds to one of the four exterior walls. The GSLEdit file used for Super House C describes the triple paned, argon filled window with two low-e coatings shown in Figure 2.7c. This is the same window used for the simulations using static shading. One control loop is set up for each exterior wall of the house for a total of four control loops. Each control loop controls the shading for all the windows in a given wall.

The shades in each CFC type are activated based on the intensity of solar radiation measured in W/m^2 on the corresponding exterior wall. One day type for each day of the year was set up, and three control periods for the day were set up to allow the blinds to be closed during the night and then opened during the day unless the insolation reaches the setpoint that triggers the blinds to close. The control period setpoints and control laws are summarized in Table 2.10.

Table 2.10: Control period inputs for dynamic shading model

Control period	**1 (00h00 to 07h00)**	**2 (07h00 to 22h00)**	**3 (22h00 to 24h00)**
Sensed property	Solar radiation on surface	Solar radiation on surface	Solar radiation on surface
Actuated property	Slat angle	Slat angle	Slat angle
Control law	Basic control	Basic control	Basic control
Shade on (W/m^2)	500	500	500
Shade off (W/m^2)	400	400	400
Slat angle (closed)	0.0 °	80.0 °	0.0 °
Slat angle (open)	85.0 °	0.0 °	85 °

The first period begins at midnight and ends at 07:00. During this time the blinds are closed for privacy. The second period begins at 07:00 and ends at 22:00. During this time the blinds are open unless the solar radiation on the wall in which the window is installed reaches the setpoint which causes the blinds to close. The final period begins at 22:00 and ends at midnight. During this time the blinds are closed again and remain closed regardless of insolation.

In order to close the blinds overnight, the “open” and “closed” angles had to be reversed. During the two overnight control periods, the “open” angle was set to 85.0 ° from horizontal.

The simulation for Super House C returns to the original occupancy and casual gains schedule, with only two occupants in the house. Both occupants leave the house between 08:00 and 17:00 on weekdays. The schedule for the blinds and the occupancy schedule do not line up exactly, but this allows the effect of the dynamic shading control to be examined and compared to the other simulations.

2.5.3 Single Control Setpoint

The final variation on the Toronto house to be simulated is Super House D. For this simulation the heating and cooling setpoints are set to a single value, as is the relative humidity. Unlike the other houses there is no dead band between the upper and lower setpoints. For this simulation the heating and cooling setpoints were both set to 22 °C, and the humidity control system was set up to maintain a constant relative humidity of 55%. No other changes were made to the house or the occupancy and casual gain schedules for this variation.

2.5.4 Different Climate Zones

In order to determine how the loads in an energy efficient house will be affected by other climates within Canada, four simulations of Super House A were run. Super House A is the base case for the energy efficient houses studied, with two occupants, static shading, and a range of setpoints.

Canadian Weather for Energy Calculation (CWEC) files for Calgary, Vancouver, Winnipeg, St John’s, Shearwater, Toronto, Quebec City, Saskatoon, and Whitehorse are included as standard ESP-r climate files. Other CWEC files are available from the U.S. Department of Energy. For this study, houses in Vancouver, Winnipeg, Shearwater, and Whitehorse were simulated, representing a wide range of climates across Canada.

Geographic information for the locations simulated is compiled in Table 2.11. All values for longitude refer to the distance from the standard longitude for that location. Longitudes marked as “W” are entered into ESP-r as negative values. The CWEC files for Vancouver, Winnipeg, and Whitehorse all use 2001 as the climate year, while Shearwater uses 1973 data.

Table 2.11: Location information for different climates within Canada

House Location	**Latitude**	**Longitude**	**Weather Station**	**Description of Climate**
Vancouver, British Columbia	49.18 °N	3.17 °W	Vancouver International Airport	Mild, humid
Winnipeg, Manitoba	49.9 °N	7.23 °W	Winnipeg International Airport	Cold, dry
Shearwater, Nova Scotia	44.63 °N	3.5 °W	CFB Shearwater	Moderate, humid
Whitehorse, Yukon	55.90 °N	4.15 °W	Whitehorse Airport	Subarctic, dry

A new variant of Super House A was created for each location and a simulation was run using the same settings as those that were run using the Toronto CWEC file. No changes were made to any of these houses apart from the location and the climate files.

2.6 Validation of Model

To confirm that the sensible heating loads found using simulation were within reason, the sensible heating loads for each scenario were estimated using the degree-day method. The degree day method is a method used to estimate the amount of fuel required to provide sensible heating for a building. This is not the most accurate method of estimating energy use by a house - it requires many assumptions, and the degree day values have not changed since the method was developed. The degree day method also does not reflect changes in construction practices and what is considered comfortable for occupants, nor does it take into account other factors such as heat generated within the house by appliances, occupants, or other internal gains. However, for the purposes of this study, the degree-day method was considered an acceptable method of checking that the results from the simulation were within the right order of magnitude.

The method for determining the number of degree days is described in the ASHRAE Handbook of Fundamentals and [McQuiston et al., 2005]. For Toronto, the number of heating degree days is 3892 $°C - days$ [Fundamentals, 2009]. The degree-day method calculates FH, which is the total $kWhrs$ of sensible heat output needed to balance the heat loss through assembly components throughout the year. This value is based on the number of heating degree days at the location of the project.

To calculate FH for each envelope assembly, the first step is to determine the heat loss per degree of temperature change, UA, for each assembly (walls, floor slab, roof, windows). U is the U-value for that particular assembly in $W/(m^2K)$, based on the thermal insulation levels of the materials used. A is the total area of that assembly used in the house construction in m^2.

Calculation of UA for each construction assembly is done for each type of envelope assembly in the house - the roof, the walls, the floor slab and the windows. The value of U is the reciprocal of RSI for that assembly, where RSI is the R-value in metric units.

$$U = \frac{1}{RSI} \tag{2.2}$$

Once UA values are calculated, FH is calculated for each assembly.

$$FH = \frac{(24 * DD * C_d * UA)}{1000} \tag{2.3}$$

In Equation 2.3, DD is the number of degrees for the location. C_d is a correction factor and a value of 0.66 was used. This correction factor is for degree days based on a balance temperature of 18 °C.

The final FH term needed for the validation is the FH term for ventilation and infiltration. This is a rough estimate only and is based on the rate at which air enters the house. For this FH term, the value UA is found using Equation 2.4. In Equation 2.4, Δh is the change in enthalpy in kJ/kg_{air} and ΔT is the temperature change in K.

$$UA = \frac{(V\Delta h)}{(\rho\Delta T)} * 1000 \tag{2.4}$$

Once all the values of FH are calculated, they are summed to find the total $kWhrs$ required to counteract the heat lost from the house throughout the year.

Table 2.12 summarizes results for the 1970's house. While the degree-day calculation was also performed for the 2006 house and the Super House, the limitations of the calculation result in large discrepancies when the results are compared to the simulations, and those results are not presented here.

Table 2.12: Validation calculations for houses

House	**1970's House**
Degree Day Calculation ($kWhrs$)	14851.2
Energy Delivered for Sensible Heating from ESP-r simulation ($kWhrs$)	10460.4

There are several possible reasons for the discrepancy between the degree-day calculation and the ESP-r simulation results. The degree-day method does not take into account any thermal mass within the house. The degree-day calculations presented also assume that the floor slab is elevated while in the ESP-r simulations the floor slab is directly on the ground.

Thermal mass refers to the ability of a building to store heat within the materials used in it's construction. Materials that are high thermal mass include concrete, rock, and soil. Thermal mass stores heat within itself during warm periods and then releases it at times when the heat is needed. While thermal mass is an entirely passive method of reducing energy use within homes, when done well it can be extremely effective at reducing both heating and cooling loads within the house. For example, the sun shining on a concrete floor during the afternoon will warm the concrete. After the sun goes down the heat stored in the concrete will be released into the conditioned space of the house, reducing the required heating load. Thermal mass can also be effective at reducing seasonal peaks.

Finally, the tabulated heating degree days used are calculated using a balance point temperature T_{bal} of 18.3 °C. The balance point temperature is "the value of the outdoor temperature T_0 at which, for the specified value of the interior temperature T_i, the total heat loss q_{gain} is equal to the heat gain from sun, occupants, light, and so forth" [ASHRAE, 2009b]. The T_{bal} of 18.3 °C is not appropriate for the house constructions examined in this thesis.

Despite these discrepancies, the degree-day method calculations demonstrate that the simulation results are giving reasonable results. For comparison, the simulations of the

Juneau house run in 2006 for the Habitat Congress Building America resulted in 18130 BTU-hours of energy consumed, which is approximately equivalent to 5.31 kWhrs [Building Science Corporation, 2006]. Juneau has 4629 heating degree-days per year [Fundamentals, 2009].

Chapter 3

Data Analysis

3.1 Introduction and the Psychrometric Chart

The psychrometric chart is a graphical representation of the thermodynamic equations of state for moist air, and allows different air conditioning processes to be visualised. Various psychrometric charts for a range of situations are available. In this section, the procedure for plotting psychrometric charts and plotting data from the ESP-r simulations will be detailed.

The plots described in this section, called rosettes, are generated by drawing a load line based on the sensible and latent equipment loads at each timestep in an annual simulation. Each load line is a representation of the equipment load that is required to bring the indoor temperature and relative humidity to the desired setpoint. A longer load line shows that more energy is required.

The rosette in Figure 3.1 shows possible load conditions that may be present at any given timestep. The angle of each load line is determined by the ratio of sensible to latent equipment loads at that timestep. The head of each arrow in Figure 3.1 represents the setpoint that the HVAC system must maintain. This setpoint is indicated by the dot on Figure 3.1.

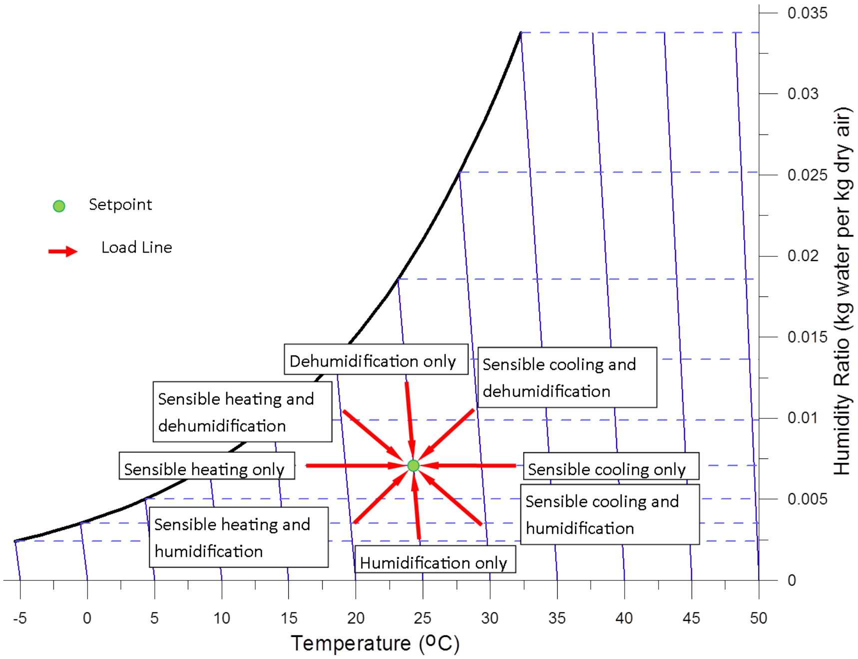


Figure 3.1: Load lines showing different possible load conditions on a psychrometric chart

The load condition that is present at any given timestep will depend on the outdoor weather condition and the heat and moisture sources within the house. For the simulations based on the Toronto climate, heating and humidification is expected during the winter and cooling and dehumidification is expected during the summer. During the shoulder seasons it is expected that the loads will be smaller and the direction of each load line will be more variable.

In addition to plotting the simulation data on psychrometric charts, the data will be plotted in a similar but more straightforward way on a Cartesian plane. These plots will also be discussed in this chapter.

3.2 Plotting the Psychrometric Chart

To quickly see any differences between houses and to assess the effects of different energy efficiency measures and other changes to the house models, simulation data was exported from ESP-r and plotted directly on a psychrometric chart. There are many commercial software packages available that will plot condition points and load lines on standard psychrometric charts. For this research it was preferable to have the psychrometric chart plotted in a widely used graphing program that can be scaled depending on the length of the equipment load lines or otherwise modified to best present large amounts of data. All plotting work in this study was done using Grapher, but any plotting program that allows for multiple plots to be overlaid and is able to create vector plots could be used to produce similar plots. In this section, X, Y, and Z will refer to the axes on the plots as shown in Figure 3.2.

3.2.1 Axes and Scaling Factors

The psychrometric chart used to display the data is plotted by translating enthalpy (h) and humidity ratios (ω) into X and Y co-ordinates. These co-ordinates allow the psychrometric chart to be plotted, and are also used to plot the equipment load lines.

On a psychrometric chart the two independent variables are enthalpy (in kJ/kg of dry air) and the humidity ratio (in kg of water per kg of dry air). The humidity ratio is the Y axis on a psychrometric chart, but the enthalpy axis does not correspond to the X axis. Instead, the enthalpy axis is at an angle, θ, where θ is the angle between the Y axis and the enthalpy axis. The X axis on a psychrometric chart shows the dry bulb temperature for dry air ($\omega = 0$). Isotherms are not perpendicular to the X axis. The X, Y, and Z axes are shown in Figure 3.2. The Z axis, representing enthalpy, lies in the X-Y plane, and constant h lines run perpendicular to this axis.

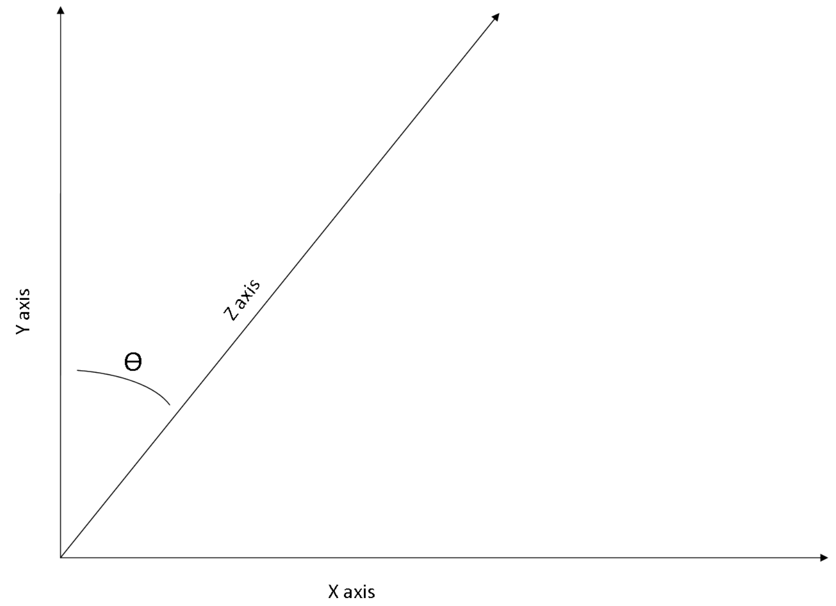


Figure 3.2: Location of the X, Y, and Z axes on the psychrometric chart

The X and Y axes show the co-ordinates of each point, x and y. There are two scaling factors required to plot the axes, b_y and b_z. An angle θ of approximately 25 ° is also needed. The scaling factors for the plots presented in this study were chosen based on the physical length of each axis in Grapher, and the maximum values of ω and h that had to be plotted.

The first scaling factor to be found is b_y, using Equation 3.1, based on ω, which is proportional to y.

$$\omega = b_y y \tag{3.1}$$

The second scaling factor, b_z is found similarly using Equations 3.2 and 3.3. Equation 3.2 gives the length of the Z axis based on θ. The location of $h = 0$ on the Z axis must meet the X axis at $T = 0\,°\mathrm{C}$ and $\omega = 0$.

$$z = \frac{y}{cos\theta} \tag{3.2}$$

$$h = b_z z \tag{3.3}$$

A final parameter b_x is also calculated, but is not used to plot any of the features of the psychrometric chart. It can, however, be used to find the intersection of a constant enthalpy line with the X axis.

$$b_x = b_z sin\theta \tag{3.4}$$

The parameters that were used for the psychrometric charts in this study are compiled in Table 3.1.

Table 3.1: Summary of scaling factors for plotting psychrometric chart

$\boldsymbol{\theta}$	$\mathbf{b_x}$	$\mathbf{b_y}$	$\mathbf{b_z}$
31 °	$0.3126\frac{°\mathrm{C}}{mm}$	$0.00019685\frac{kg_{water}/kg_{air}}{mm}$	$0.607\frac{kJ/kg_{air}}{mm}$

3.2.2 Plotting the Psychrometric Chart Features

To plot a point on a psychrometric chart, two values are required. For the psychrometric charts plotted here, ω and h are used. Equations for ω and h are found in any undergraduate building science textbook and are reproduced here as Equations 3.5 and 3.6.

$$\omega = 0.6219 * \frac{P_v}{(P_{atm} - P_v)} \frac{kg_{water}}{kg_{air}} \tag{3.5}$$

$$h = T + (\omega * (2501.3 + (1.86 * T))\frac{kJ}{kg_{air}} \tag{3.6}$$

In Equation 3.6, T is the dry-bulb temperature in degrees Celcius. In Equation 3.5, P_{atm} is the barometric pressure, and P_v is the partial pressure of water in the air.

Given b_x, b_y, b_z, and θ for the psychrometric chart, once ω and h are known x and y can be calculated for that point using Equations 3.7 and 3.8. Now the psychrometric chart can be plotted.

$$x = \frac{h}{b_z} sin\theta + \frac{\frac{h}{b_z} cos\theta - \frac{\omega}{b_y}}{tan\theta} \tag{3.7}$$

$$y = \frac{\omega}{b_y} \tag{3.8}$$

Saturation Curve

When the relative humidity (RH) is 100%, air is saturated. The saturation curve on a psychrometric chart is created by plotting the humidity ratio at a relative humidity of 100% for a range of dry bulb temperatures [McQuiston et al., 2005].

The saturation pressure of water, P_s, is calculated for dry bulb temperatures from $-5\,°C$ to $35\,°C$ using Equation 3.9. The constants in this equation are taken from Chapter 1 of the 2009 ASHRAE Handbook of Fundamentals and T is the dry-bulb temperature in Kelvin. P_s is in kPa.

$$\begin{aligned} P_s = EXP((\frac{-5800.22}{T}) + 1.391499 + (-0.04864 * T) + ((4.14748 * 10^{-0.5}) * (T^2)) \\ +((-1.44521 * 10^{-0.8}) * (T^3)) + (6.5459673 * ln(T)))(kPa) \end{aligned} \tag{3.9}$$

Once P_s is found for a given dry bulb temperature, ω and h for that temperature are found using Equations 3.6 and 3.5, a barometric pressure of 101.325kPa, and $P_v = P_s$. Once these are known, x and y are found using Equations 3.7 and 3.8. The X and Y co-ordinates, x and y, are plotted on the psychrometric chart and these points are joined together to create the saturation curve as shown in Figure 3.3.

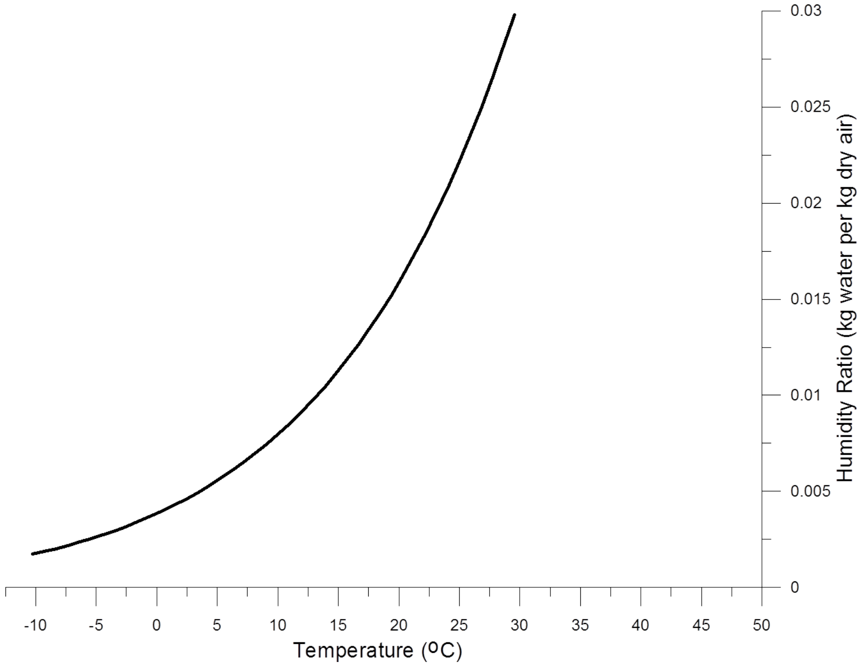


Figure 3.3: Psychrometric chart showing saturation curve

Isotherms

Isotherms can be shown on the psychrometric chart. These lines are neither vertical nor parallel to each other. To plot an isotherm, the locations of two points are needed, one point on the saturation curve and one point on the X axis. The co-ordinates of the points on the saturation curve are already known. To find the corresponding points on the X axis, for the desired temperatures from $-5\,^{\circ}\mathrm{C}$ to $35\,^{\circ}\mathrm{C}$, ω is set to zero and $h(T, \omega = 0)$ is calculated using Equation 3.5. Note that $h(T, \omega = 0)$ is numerically equal to T; see Equation 3.6.

X and Y co-ordinates of each point with $\omega = 0$ are found using Equations 3.7 and 3.8. Now there are two known points for each temperature, one on the saturation curve and one on the X axis. An isotherm is drawn between the two points.

The angle between the isotherms and the X axis will depend on the choice of θ, and changing θ will in turn change the ratio between b_x and b_z. Some trial and error was necessary to determine the best angle to use, and eventually the angle of $\theta = 31\,^{\circ}$ was selected. A psychrometric chart with the isotherms added is shown in Figure 3.4.

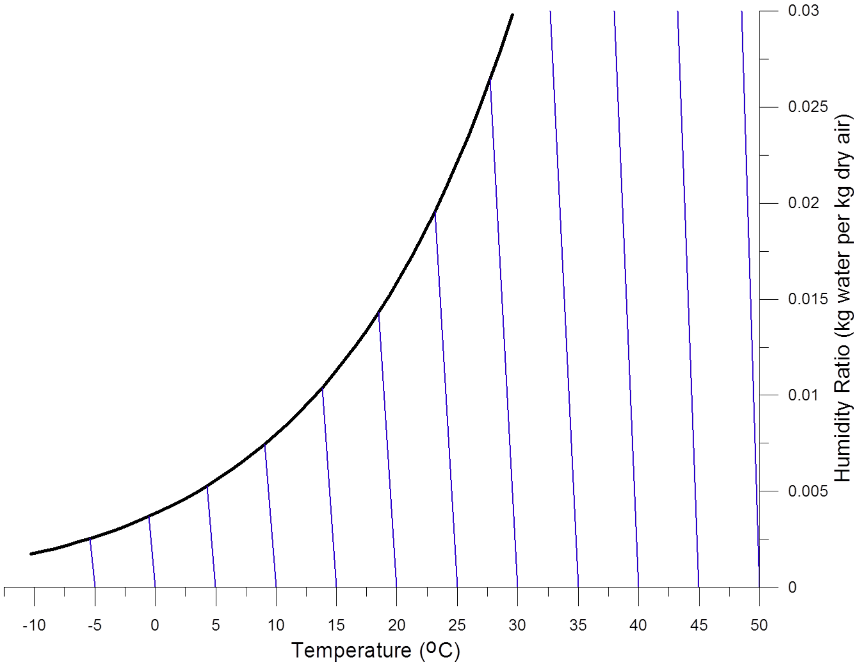


Figure 3.4: Psychrometric chart showing saturation curve and isotherms

Constant Humidity Lines

Horizontal lines from the saturation curve to the Y axis show constant humidity ratio, ω. These lines were drawn using a procedure similar to the one used for drawing the isotherms.

The X and Y co-ordinates of the points on the saturation curve that were used to draw the isotherms are already known. For each of the points used to draw an isotherm, a corresponding point on the Y axis will be found. This will give unevenly spaced constant ω lines as shown in Figure 3.5. If evenly spaced lines were desired, these could be found by choosing y, and then solving Equation 3.8 for ω. Once ω is known, Equation 3.5 can be rearranged to obtain P_v. At 100% RH, P_v is equal to the saturation pressure P_s.

The completed psychrometric chart

Once the constant ω lines have been plotted, the psychrometric chart is considered complete for this study and is shown in Figure 3.5. There are other properties that may be shown on commercial psychrometric charts including relative humidity, wet bulb temperature, the specific volume of dry air, and enthalpy. These lines were not plotted on the charts used in this study because they were not of direct interest.

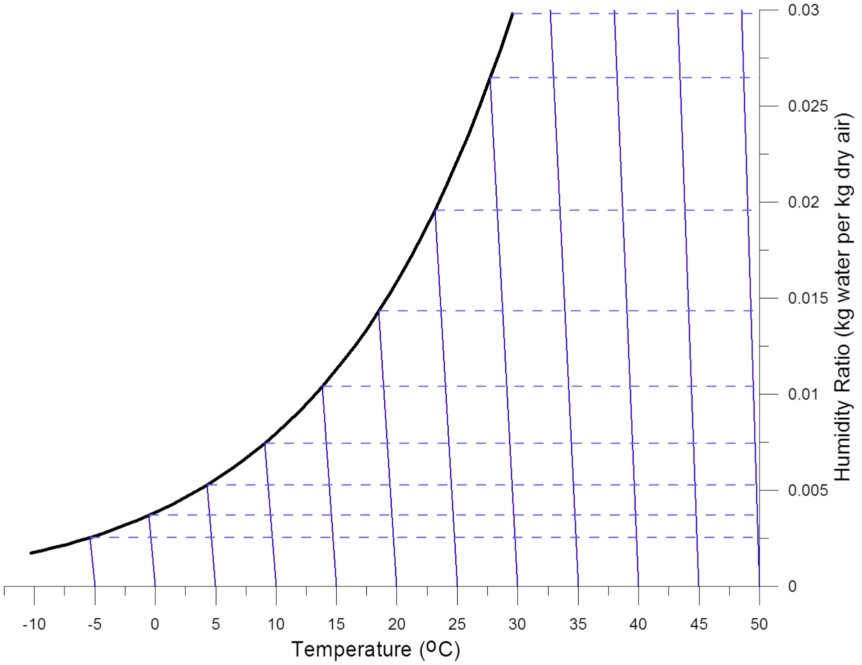


Figure 3.5: Psychrometric chart showing saturation curve, isotherms, and lines of constant ω for $b_y = 0.00019685$, $b_z = 0.607$, and $\theta = 31\,^\circ$

3.2.3 Plotting the Simulation Data

Eleven sets of data were exported from ESP-r to create the rosette for each simulation, shown in Table 3.2. These data were then overlaid on a psychrometric chart. The exported simulation data was used to draw the equipment load lines, which were then plotted as a vector plot with one load line for each timestep. One end of each vector is the temperature and *RH* setpoint that the HVAC system must meet. The other end represents the load that the HVAC equipment must meet to maintain the space conditions.

Table 3.2: Data extracted from ESP-r simulations

Property	**Unit**
Timestep	N/A
Ambient temperature	°C
Relative humidity	%
Zone dry bulb temperature	°C
Zone relative humidity	%
Sensible heating loads	kW
Sensible cooling loads	kW
Total sensible loads	kW
Dehumidification loads	kW
Humidification loads	kW
Total latent loads	kW
Total sensible and latent loads	kW

To plot the data on the psychrometric chart and create the rosettes, a mass flow rate is needed for the calculations. This flow rate acts as a scaling factor for the length of the load lines. The value of the mass flow rate is chosen based on what makes the rosette easy to read. A mass flow rate of $0.8 kg_{air}/s$ was used for all the rosettes produced as part of this study. Using the same mass flow rate for two or more simulations produces rosettes that can quickly be compared to see the changes in equipment loads.

The humidity ratio, enthalpy, and temperature at the end of the load line are found by first considering the latent equipment load alone, and then the sensible equipment load alone. The load point represents the temperature and humidity ratio at which air would enter the conditioned space at the assumed mass flow rate.

To calculate the properties at each timestep, additional atmospheric pressure data is needed. These values are taken from Environment Canada's weather monitoring data collected from weather stations across Canada. The weather data for the houses located in Toronto is taken from the weather station at Toronto's Pearson International Airport. Atmospheric pressure data from 2001 is used, since 2001 was the year simulated in ESP-r. A constant atmospheric pressure of $101.325 kPa$ could also be used as an approximation.

To draw a load line on the psychrometric chart, three points are needed: the condition point, the transition point, and the load point, as shown in Figure 3.6. The length and angle of each load line are determined by the equipment loads on the house zone. Because there are both sensible and latent loads on the equipment, a transition point must be found before drawing the load line. This transition point, shown in Figure 3.6, and is an intermediate point between the condition point and the load point. The condition point is located first, and then from there, the transition point is found by considering the latent load alone, and then the load point is found by considering the sensible load alone. This creates a triangle on the psychrometric chart. The hypotenuse of this triangle is the equipment load line for the timestep.

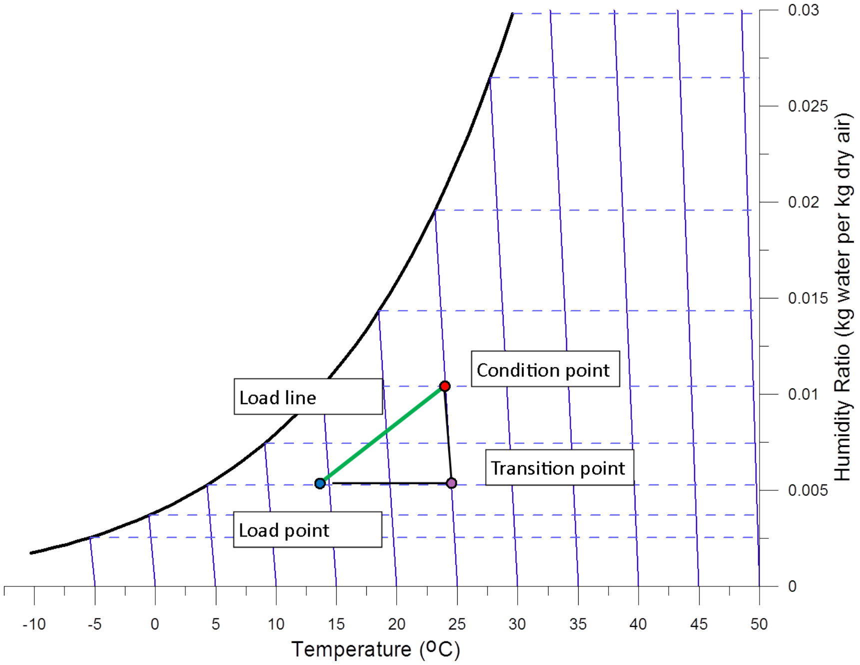


Figure 3.6: Psychrometric chart showing condition point, transition point, load point, and load line

The first step in plotting a load line is to locate the condition point on the psychrometric chart. The condition point is the temperature and RH to which the HVAC equipment must condition the zone. To locate the condition point, the first value needed is the condition humidity ratio, $\omega_{condition}$, which is found using Equation 3.5 with RH less than 100% taken into account ($P_v = RH * P_s$). Equation 3.10 uses the RH of the conditioned space, $P_s(T)$, and the barometric pressure at that timestep, P_{atm}. The saturation pressure P_s at each timestep is calculated using Equation 3.9 using the house temperature at that timestep.

$$\omega_{condition} = 0.6219 \frac{P_s(T) * RH_{house}}{P_{atm} - (P_s(T) * RH_{house})} \tag{3.10}$$

Next $h_{condition}$ is calculated using Equation 3.6, using T as the temperature of the house from the ESP-r simulation. Now, ω and h are known for the condition point, and the X and Y co-ordinates for this point can be found using Equations 3.7 and 3.8.

The transition point is located by setting $T_{transition} = T_{condition}$, since only latent heating or cooling is being considered. An energy balance on the addition or removal of moisture by the equipment gives Equation 3.11.

$$h_{transition} = h_{condition} - \frac{q_{latent}}{\dot{m}} \tag{3.11}$$

Once $h_{transition}$ has been calculated, $\omega_{transition}$ is found by solving Equation 3.6. Coordinates for the transition point do not need to be found, as this point will not be plotted.

After the transition point has been found using the latent load, the load point is found by considering the sensible load. As seen on Figure 3.6, the line from the transition point to the load point is a horizontal like representing a constant humidity ratio process, where $\omega_{load} = \omega_{transition}$. Since ω_{load} is already known, h_{load} can be found using Equation 3.12, which comes from an energy balance on the sensible heating or cooling process. In Equation 3.12, m is the assumed mass flow rate into the conditioned space, and $q_{sensible}$ is the total sensible heat added or removed by the equipment. This load does not include the load of the HRV.

$$h_{load} = h_{transition} - \frac{q_{sensible}}{\dot{m}} \tag{3.12}$$

The load point temperature is not needed to locate the tail end of the load line on the psychrometric chart, but can be calculated using Equation 3.6. The psychrometric chart is now complete and the load lines for each timestep in the simulations can be plotted.

Typical Weeks

Load lines for an entire year can be plotted, or a number of load lines can be selected to examine any period during the year. Examining an entire year's worth of data on one plot shows the relative magnitude of the loads, and the distribution of these loads. However because of the sheer volume of data produced by each simulation, if an entire year of data is on one single plot, shorter load lines will be hidden by longer lines and important information is lost. To avoid this problem, data from time periods shorter than the full year can be extracted and plotted.

A typical week from each season will be plotted. A typical week is the week with the least deviation from the seasonal values for cooling degree days (CDD), heating degree days (HDD), and solar data [Hand, 2010]. These weeks are found by using ESP-r to analyse the appropriate climate files to find the start and end dates for each typical week. This was done using a heating base temperature of 21 °C and a cooling base temperature of 25 °C, based on the setpoints for the heating and cooling systems used in the ESP-r simulations. Different climate files will have different typical weeks. The typical weeks for Toronto are shown in Table 3.3, and typical weeks for additional locations are in Appendix B. All weeks begin on Mondays unless otherwise specified.

Table 3.3: Start and end dates for seasonal typical weeks using 2001 Toronto climate data

Season	**Typical Week Start (00h)**	**Typical Week End (24h)**
Winter 1	26 February	4 March
Spring	9 April	15 April
Summer	11 June	17 April
Fall	15 October	21 October
Winter 2	17 December	23 December

3.3 Single Point Plots

To make the rosettes easier to read, all the condition points could be shifted to one single point on the psychrometric chart instead of showing a range of temperatures and humidities. Shifting the points on the psychrometric charts can be done, but a single point on a Cartesian co-ordinate system is more suitable for showing the sensible and latent loads at each timestep.

The plot in Figure 3.7 shows q_{latent} on the Y axis and $q_{sensible}$ on the X axis. Similar to the rosettes, each quadrant on the Cartesian plane of the single point plots represents a different load condition. The X and Y axes are set up with the negative and positive values as shown in Figure 3.7 so that the placement of the load lines will correspond with the rosettes on the psychrometric charts.

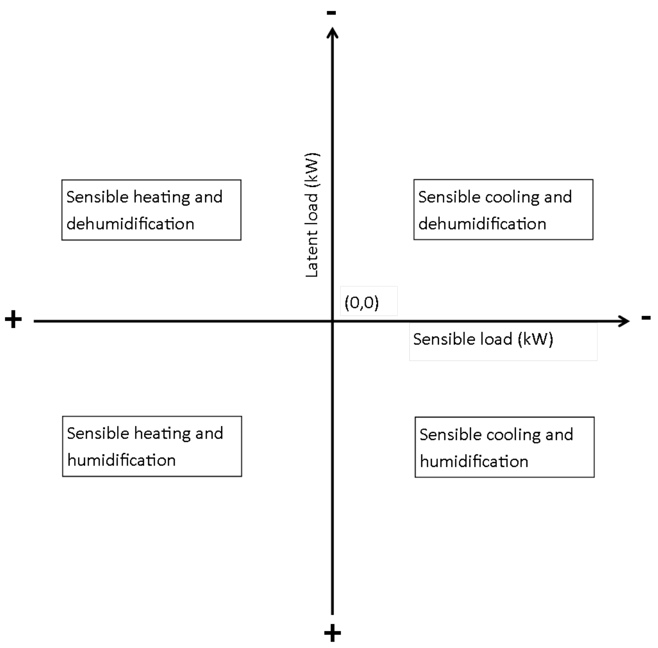


Figure 3.7: Set up for plots of load lines on Cartesian plane

The load lines on the single point plots are created by plotting a vector between the point $(q_{sensible}, q_{latent})$, and the point $(0, 0)$. Plotting the load lines shows the equipment loads as they are exported from ESP-r, with no further manipulation, and does not depend on the setpoints or on a selected fictitious conditioned space mass flow rate.

3.4 Frequency Analysis

As seen in Figure 3.1, there are nine different possible load conditions at each timestep. Eight are shown, plus no load at a given timestep is possible. The total number of timesteps with each load condition was found using Excel. The formula used for this counts all loads greater than zero, no matter how small. The total number of times each timestep occurs for each house can then be compared to see if there are any trends.

While all of the load conditions shown in Figure 3.1 are possible, this research is primarily concerned with those load conditions that have a latent component.

3.5 SHR Plots and Analysis

For each simulation the sensible heat ratio (SHR) of the equipment was calculated at each timestep using Equation 3.13. Most commercial psychrometric chart includes a protractor that shows the different sensible heating ratios. Sensible heating with humidification and sensible cooling with dehumidification will both give an SHR between 0 and 1, regardless of the relative magnitudes of the loads in question. A case with sensible cooling and dehumidification or humidification will have the SHR ranging from 0 to negative infinity or 1 to infinity, depending on the loads present.

The SHR was calculated at each timestep and plotted. Only values between -5 and 5 were plotted. An example of the resulting plot is shown in Figure 3.8.

$$SHR = \frac{q_{sensible}}{q_{total}} \tag{3.13}$$

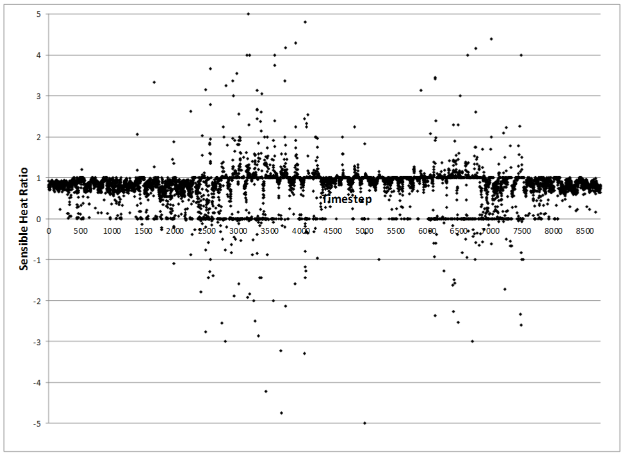


Figure 3.8: Example of the SHR plots for examination

The plot of the SHR for each timestep in the year shows where the majority of the SHR values fall in each season. The plot also shows the switch between the heating and cooling seasons, and whether the SHR at a given timestep is typical for that season, or if it is an outlier. While analysing the typical weeks for each house, the maximum and minimum SHR for each week was found, as well as the average SHR during that time period. The SHR values were then compared from house to house. This was repeated for each season.

Finding the SHR at each timestep is important for this research because it is the standard method used to compare the sensible loads to latent loads. Calculating and plotting the SHR at each timestep for each house allows for direct comparison to see whether the sensible loads or the latent loads are dominant at that timestep. While the magnitude of the sensible and latent loads may change from house, how the SHR will change is of particular interest.

Chapter 4

Simulation Results and Discussion

4.1 Results for Toronto Houses

The six houses that were modelled were described in Chapter 2. The differences are summarized in Table 4.1.

Table 4.1: Summary of houses simulated in ESP-r

House	**Description**
1970 House	Built to 1970's era construction. No HRV. Two occupants.
2006 House	Built to meet 2006 OBC. HRV. Two occupants.
Super House A	Uses twice the thermal insulation as 2006 OBC house. Reduced infiltration. HRV. Two occupants.
Super House B	Same construction as A. Four occupants.
Super House C	Same construction as A. Two occupants. Dynamic shading control loop implemented.
Super House D	Same construction as A. Two occupants. Set points changed to single temperature and relative humidity, instead of a range.

4.1.1 1970 House

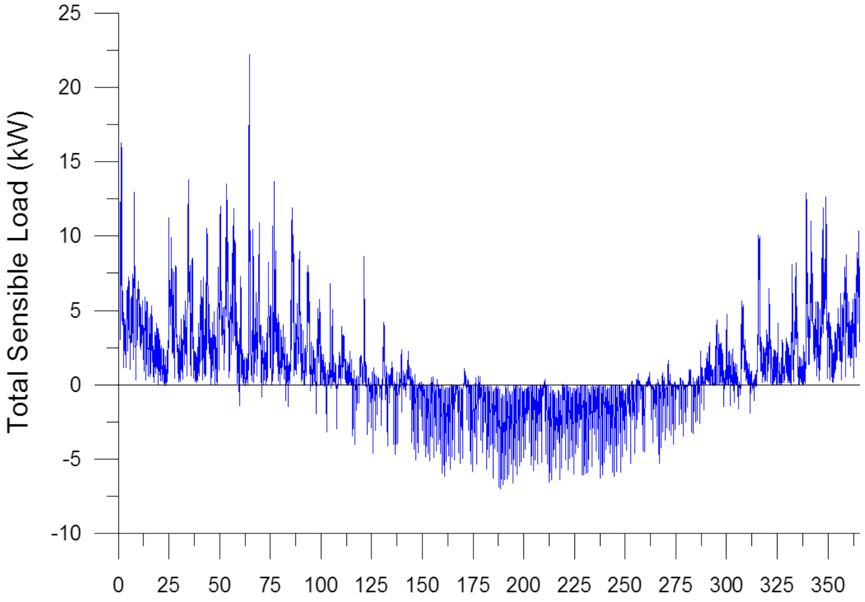
A summary of the key parameters for the model of the 1970 house is given in Table 4.2.

Table 4.2: Key parameters for simulation of 1970 house

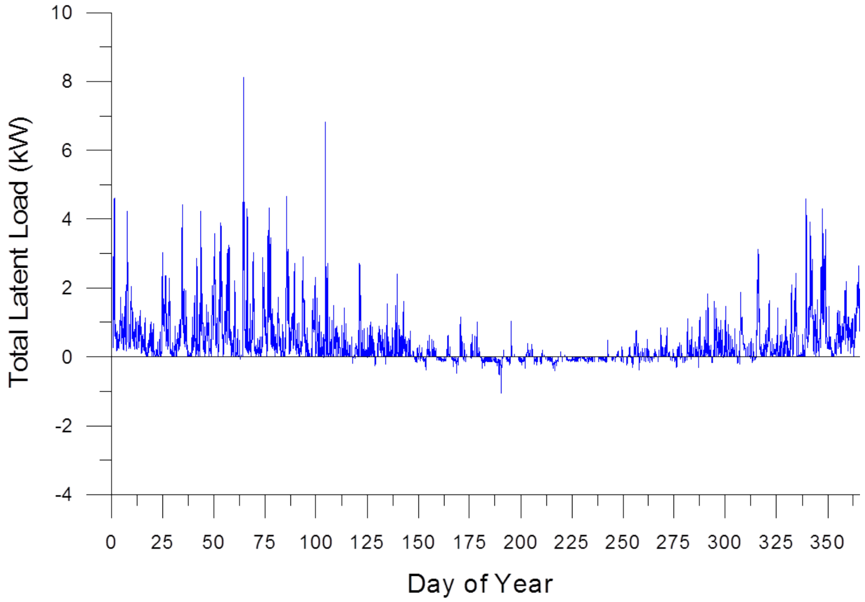
Parameter	**Value for 1970 House**
R-value, Walls $\left(\frac{ft^2 * °\mathrm{F} * hr}{BTU}\right)$	14
R-value, Roof $\left(\frac{ft^2 * °\mathrm{F} * hr}{BTU}\right)$	20
Windows	Double paned, air filled, no coatings
R-value, Floor $\left(\frac{ft^2 * °\mathrm{F} * hr}{BTU}\right)$	10
Occupants	2

The loads for the 1970 house are plotted in Figure 4.1. These plots show, left to right, the progression of the loads throughout the year from January 1st to December 31st. The peak loads for the year are shown in Table 4.3, and show that the dominant loads for this house are sensible heating and humidification. The number of times that each possible load combination occurs for the 1970 house is compiled in Table 4.4.

In Figure 4.1 and in all figures in this chapter, a negative sensible load indicates a sensible cooling load, and a negative latent load indicates a dehumidification load. If heat or moisture is being added to the space, then the load will be positive.



(a) Sensible heating and cooling loads



(b) Dehumidification and humidification loads

Figure 4.1: Space conditioning loads at each timestep for 1970 house

Table 4.3: Peak loads for the entire year for the 1970 house

Load condition	**Maximum Value (kW)**	**Total kWhr**
Sensible heating	14.1	10460.39
Sensible cooling	6.78	4863.47
Dehumidification	1.05	130.05
Humidification	8.12	3259.74

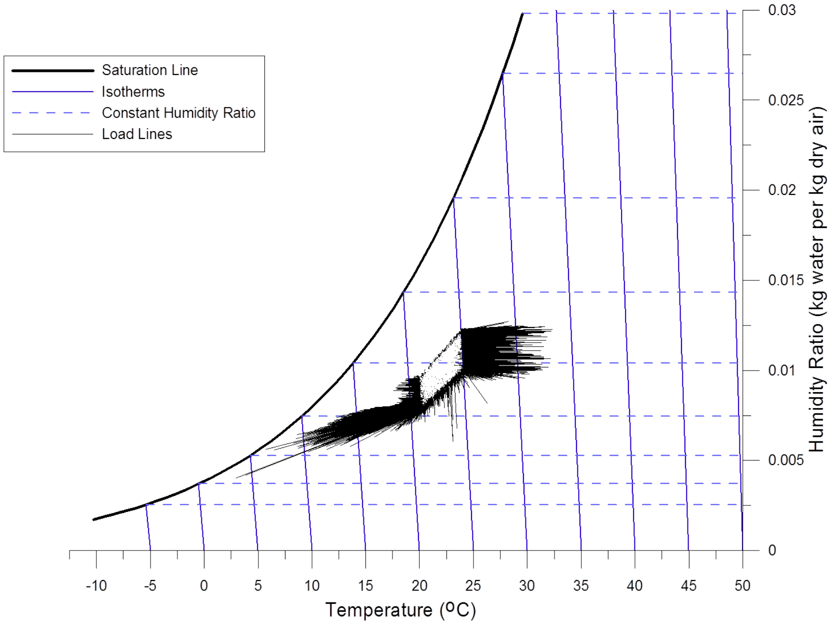
There are eight possible load combinations, including four single loads, that may be present at a given timestep, not including the situation where there are no loads at all. The number of times each of these load combinations occurs for the 1970 house is compiled in Table 4.4. The column "Days" is the number of hours each load condition occurs divided by 24. Total hours of sensible heating, sensible cooling, humidification, and dehumidification are also included in Table 4.4.

Table 4.4: Frequency of possible load conditions for 1970 house

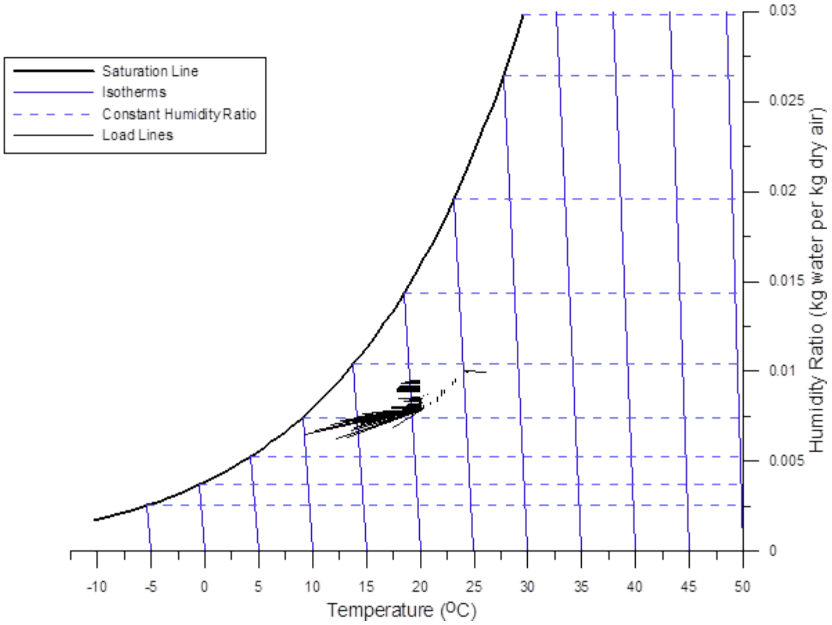
Load Condition	**Hours**	**Days**
Sensible Heating Only	534	22.25
Sensible Heating and Humidification	3814	158.92
Sensible Heating and Dehumidification	43	1.79
Sensible Cooling Only	1165	48.54
Sensible Cooling and Humidification	819	34.13
Sensible Cooling and Dehumidification	1022	42.58
Humidification Only	522	21.75
Dehumidification Only	218	9.08
All Sensible Heating	4391	182.96
All Sensible Cooling	3006	125.25
All Humidification	5155	214.79
All Dehumidification	1283	53.46

Table 4.4 shows that the loads for the 1970 house are dominated by sensible heating (4391 hours) and humidification (5155 hours). Sensible heating and humidification is the most common load combination, occurring 3814 times during the year.

The results for the 1970's house are plotted on the psychrometric chart in Figure 4.2a. The results for the entire year are shown on Figure 4.2a, and Figures 4.2b through 4.2f show the typical weeks for each season. Similarly, the single point plots are presented in Figure 4.3.

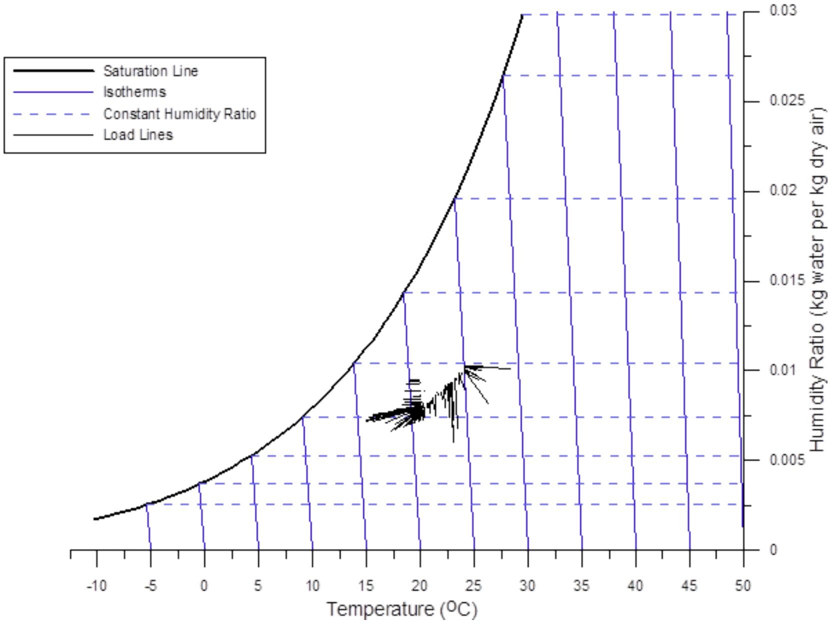


(a) Entire year

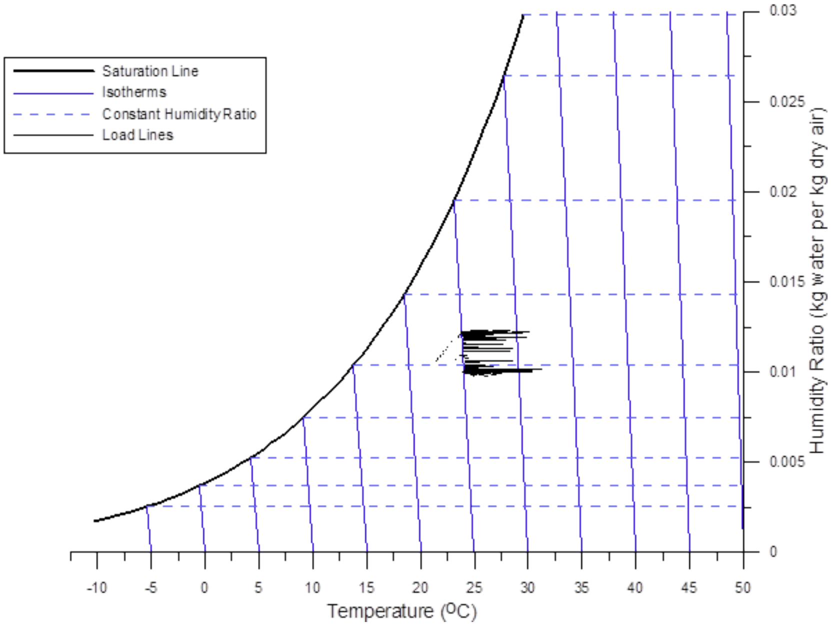


(b) Winter 1

Figure 4.2: Results from simulation of 1970 house

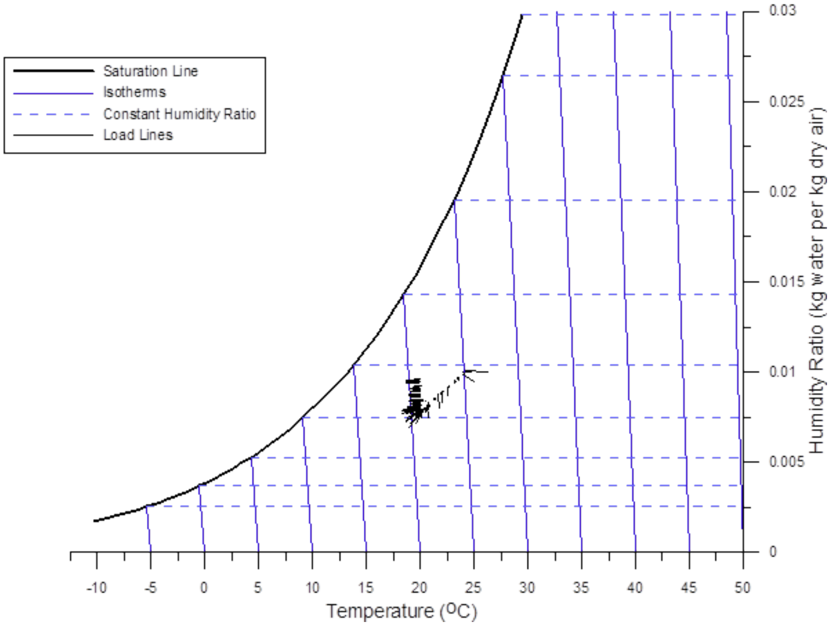


(c) Spring

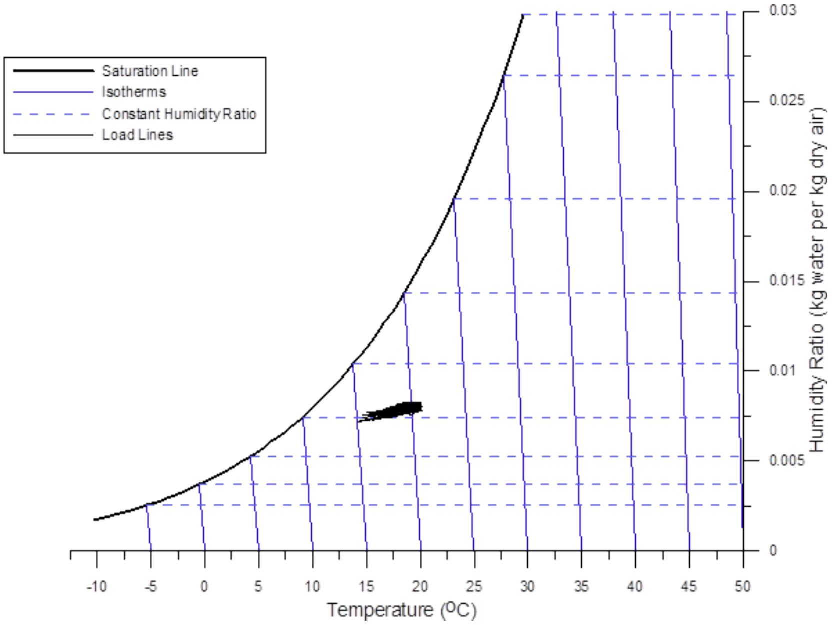


(d) Summer

Results from simulation of 1970 house

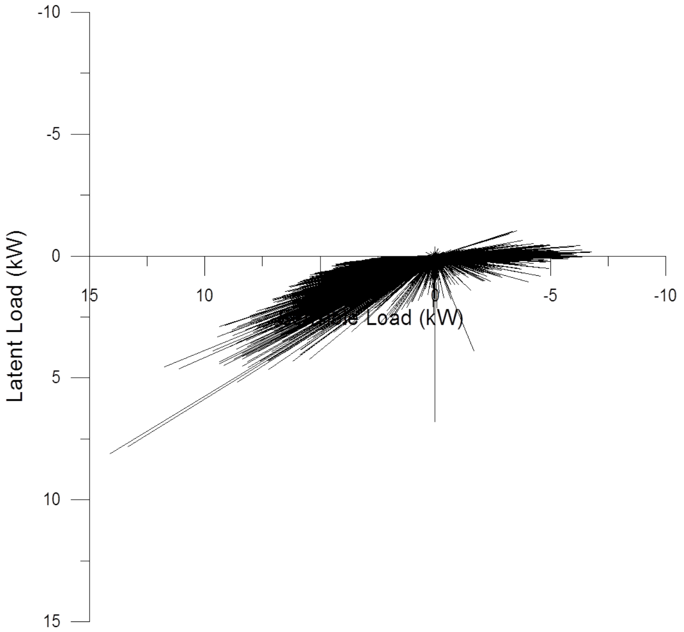


(e) Fall

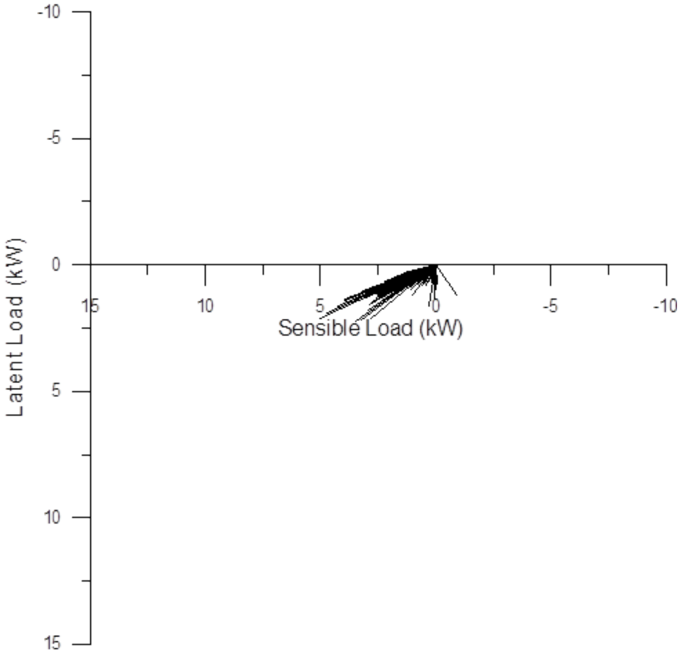


(f) Winter 2

Results from simulation of 1970 house

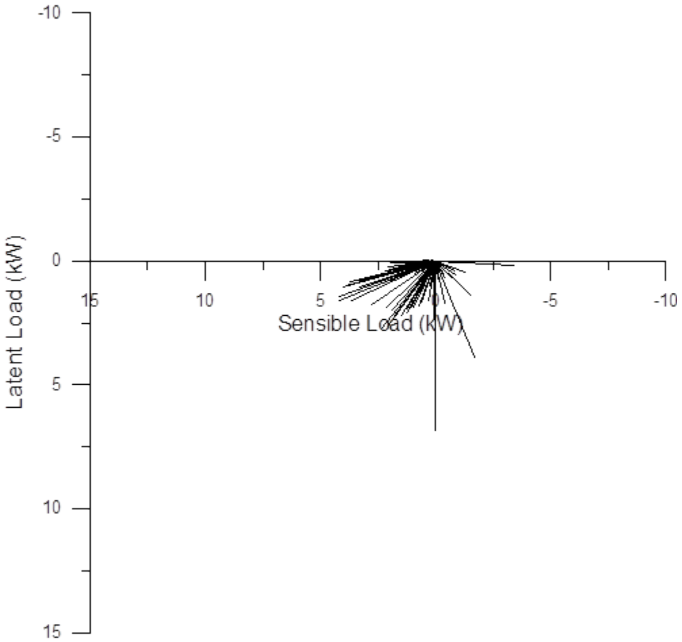


(a) Annual results

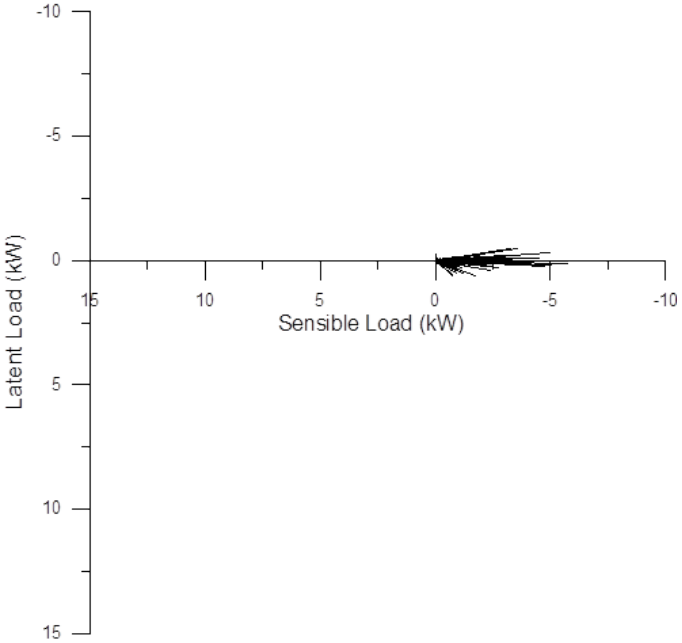


(b) Winter 1

Figure 4.3: Results from simulation of 1970 house, single point plots

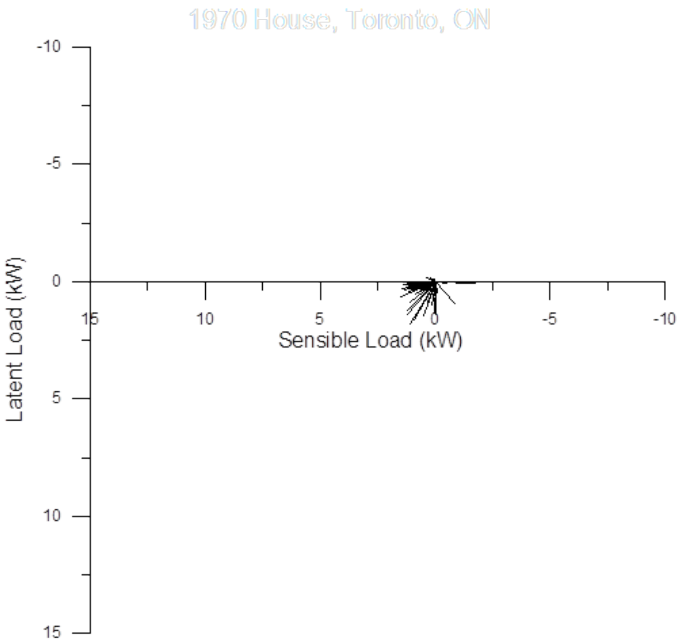


(c) Spring

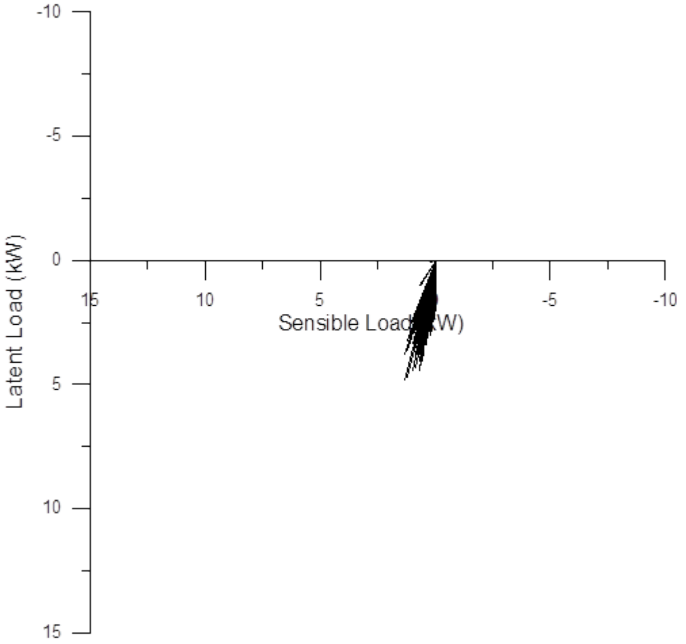


(d) Summer

Results from simulation of 1970 house, single point plots



(e) Fall



(f) Winter 2

Results from simulation of 1970 house, single point plots

The typical weeks in each season show how the load lines move around the rosette, or the origin, as the year progresses, starting out in the bottom left quadrant. Some peaks are very visible in both types of plot - there are some large sensible heating with humidification load lines shown during the winter, and a single large humidification with no sensible load shown. The plots support the conclusion above that the loads for this house are dominated by sensible heating and humidification.

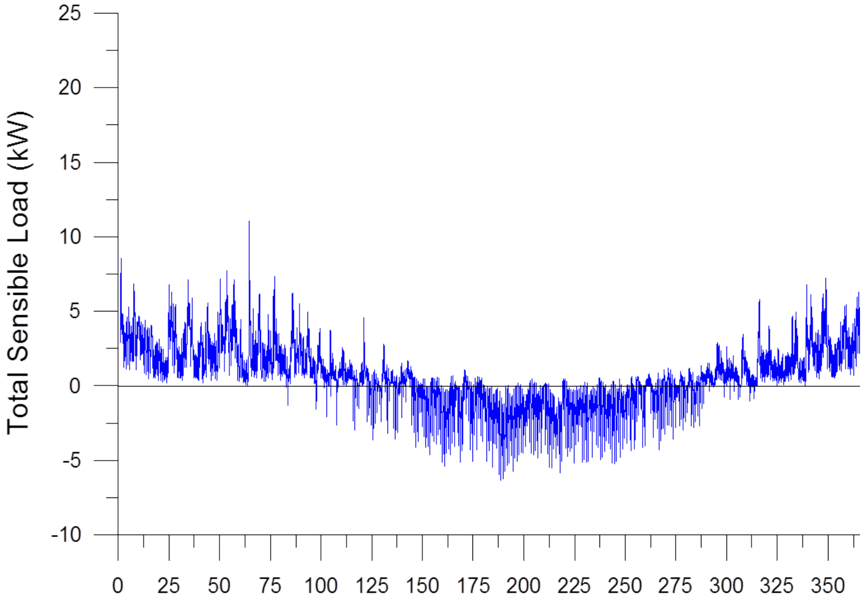
4.1.2 2006 Building Code House

The key parameters for the simulation of the 2006 Building Code House are compiled in Table 4.5.

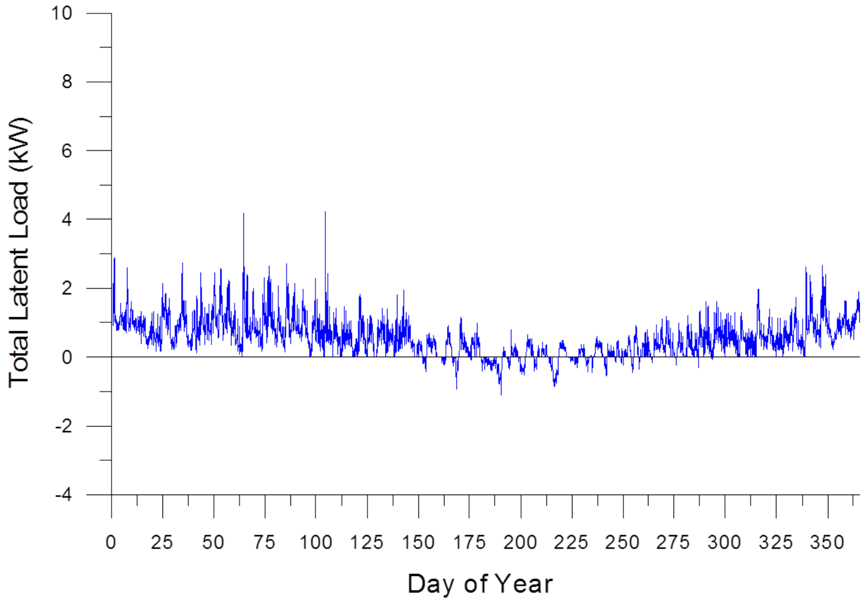
Table 4.5: Key parameters for simulation of 2006 house

Parameter	**Value for 2006 House**
R-value, Walls $\left(\frac{ft^2 * °\text{F} * hr}{BTU}\right)$	19
R-value, Roof $\left(\frac{ft^2 * °\text{F} * hr}{BTU}\right)$	28
Windows	Double paned, air filled, low-e coatings on surfaces 2 and 3.
R-value, Floor $\left(\frac{ft^2 * °\text{F} * hr}{BTU}\right)$	10
Occupants	2 adults

Figure 4.4 shows the loads for the 2006 house, showing the progression of the loads from January 1st to December 31st. Once again, sensible heating and humidification appear to be the dominant loads for this house. The frequency of each possible load combination that occurs for the 2006 house are compiled in Table 4.7.



(a) Sensible heating and cooling loads



(b) Dehumidification and humidification loads

Figure 4.4: Space conditioning loads at each timestep for 2006 house

Table 4.6: Peak loads for the entire year for the 2006 house

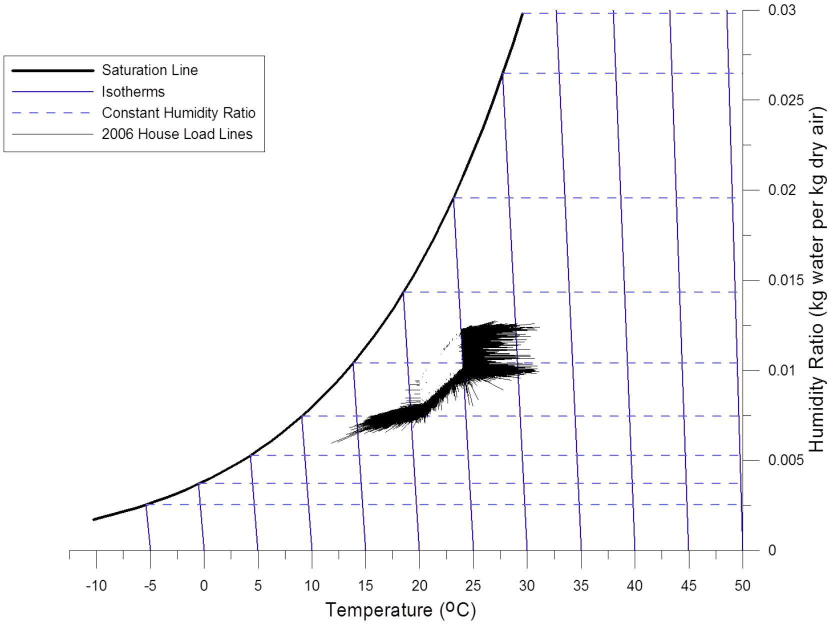
Load condition	**Maximum Value (kW)**	**Total kWhr**
Sensible heating	6.85	6087.80
Sensible cooling	5.86	4656.98
Dehumidification	1.09	199.04
Humidification	4.22	4795.81

Table 4.7: Frequency of possible load conditions for 2006 house

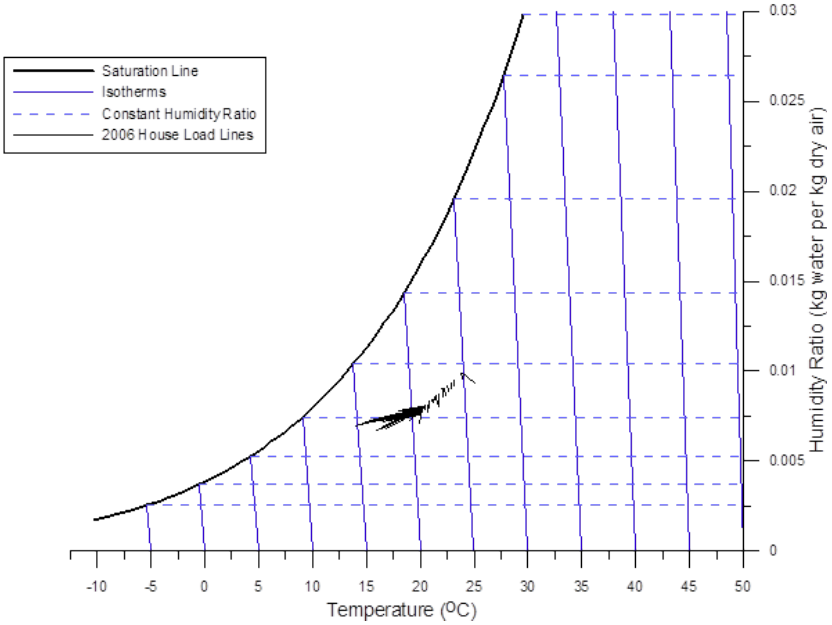
Load Condition	**Hours**	**Days**
Sensible Heating Only	24	1.0
Sensible Heating and Humidification	3862	160.92
Sensible Heating and Dehumidification	0.0	0.0
Sensible Cooling Only	709	29.54
Sensible Cooling and Humidification	1915	79.79
Sensible Cooling and Dehumidification	770	32.08
Humidification Only	1282	53.425
Dehumidification Only	23	0.96
All Sensible Heating	3886	161.92
All Sensible Cooling	3394	141.42
All Humidification	7059	294.13
All Dehumidification	793	33.04

Table 4.7 shows that the loads for the 2006 house are dominated by sensible heating (3886 hours) and humidification (7059 hours). Sensible cooling for the 2006 house is only slightly less frequent than sensible heating, occurring 3394 times during the year. Sensible heating and humidification is again the most common load combination, occurring 3862 times during the year.

The results for the 2006 house are plotted on the psychrometric chart in Figure 4.5. The results for the entire year are shown on Figure 4.5a, and Figures 4.5b through 4.5f. Similarly, the single point plots are presented in Figure 4.6.

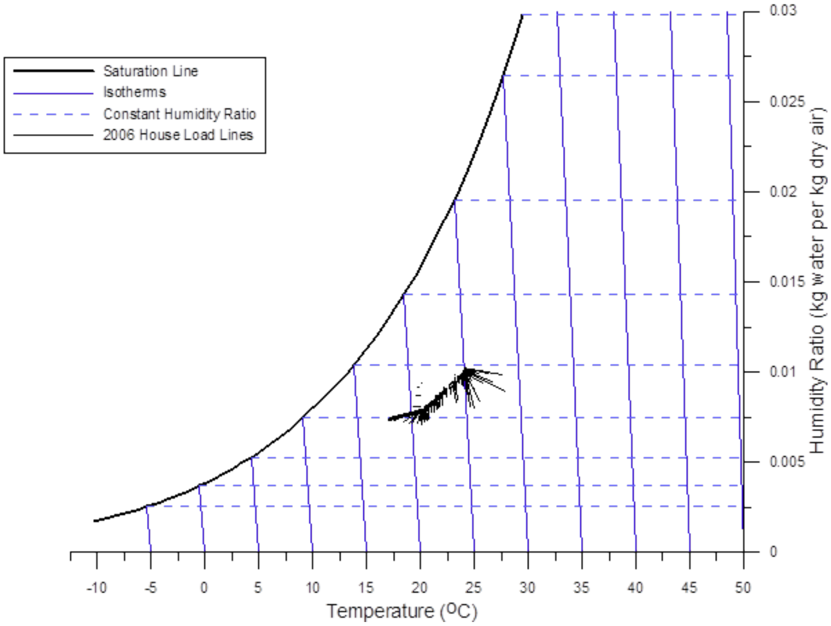


(a) Entire year

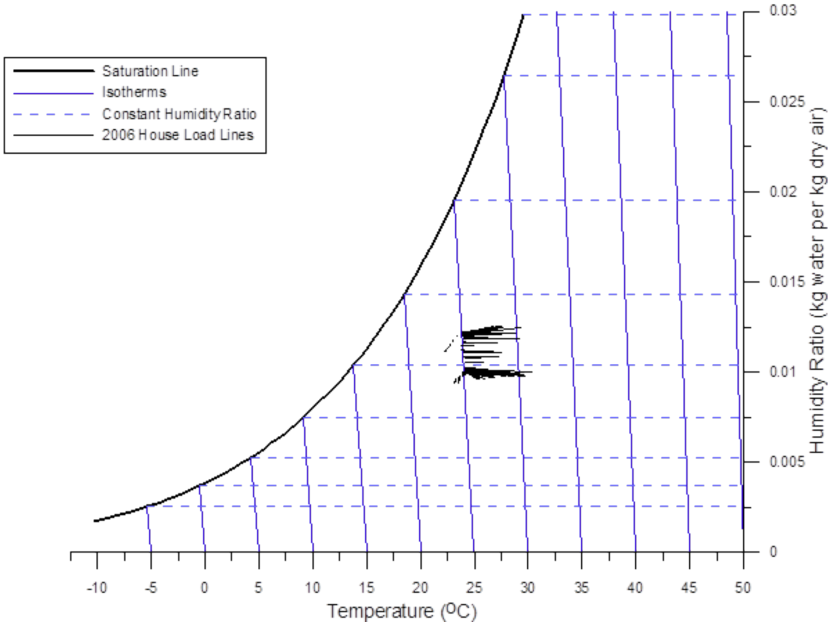


(b) Winter 1

Figure 4.5: Results from simulation of 2006 house

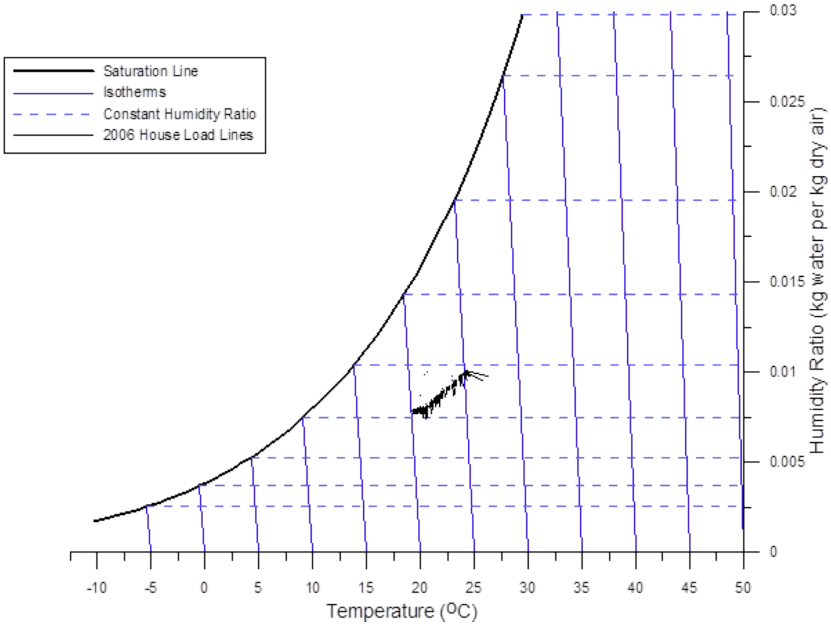


(c) Spring

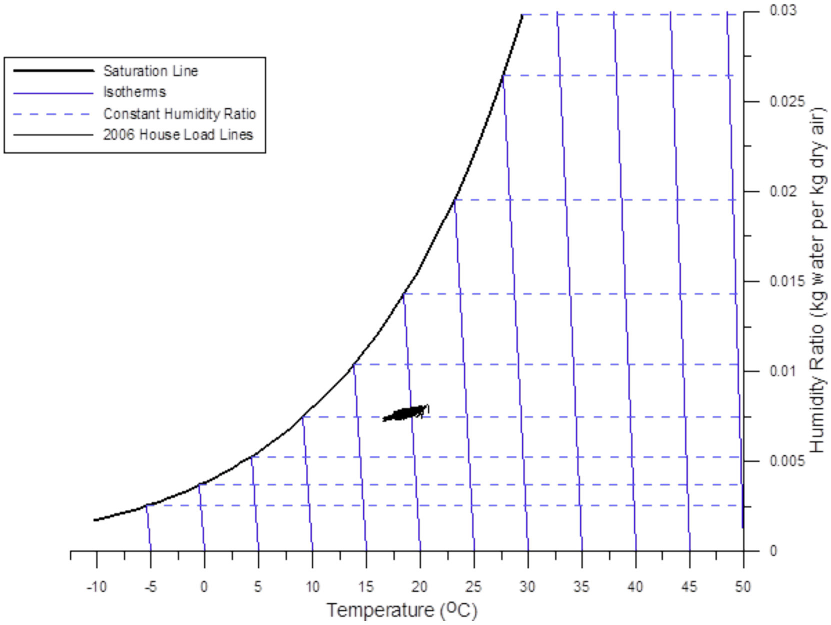


(d) Summer

Results from simulation of 2006 house

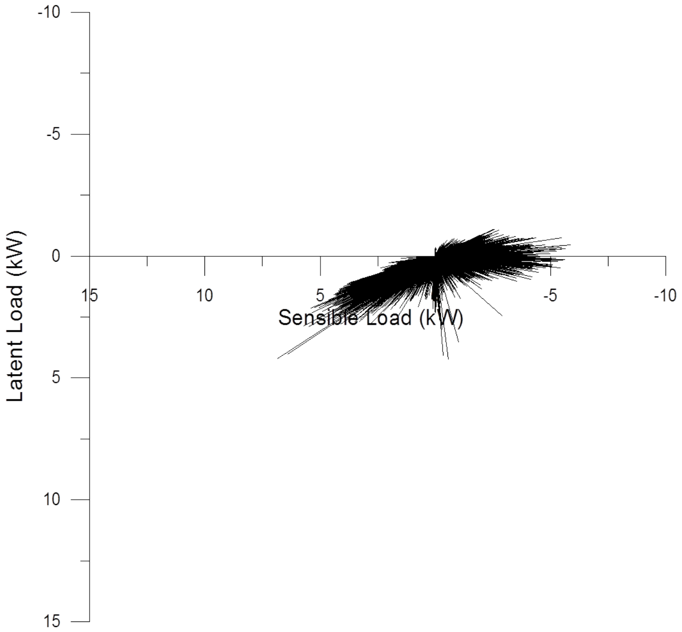


(e) Fall

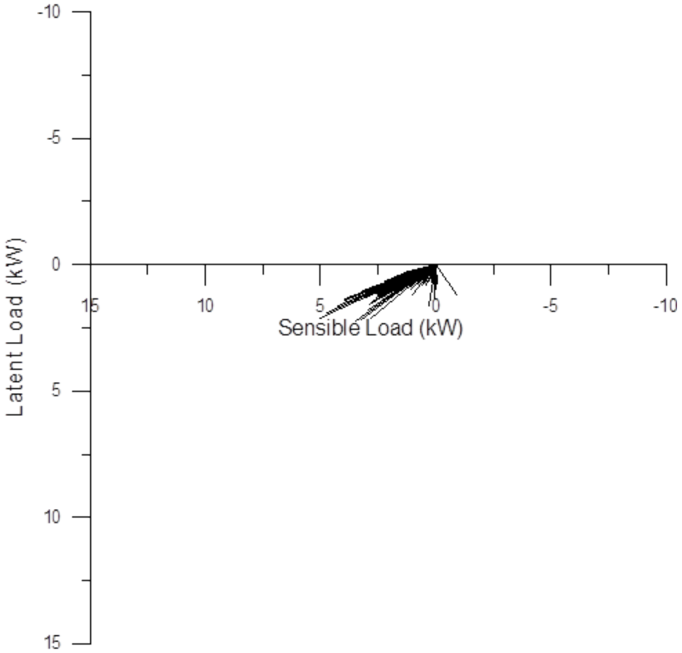


(f) Winter 2

Results from simulation of 2006 house

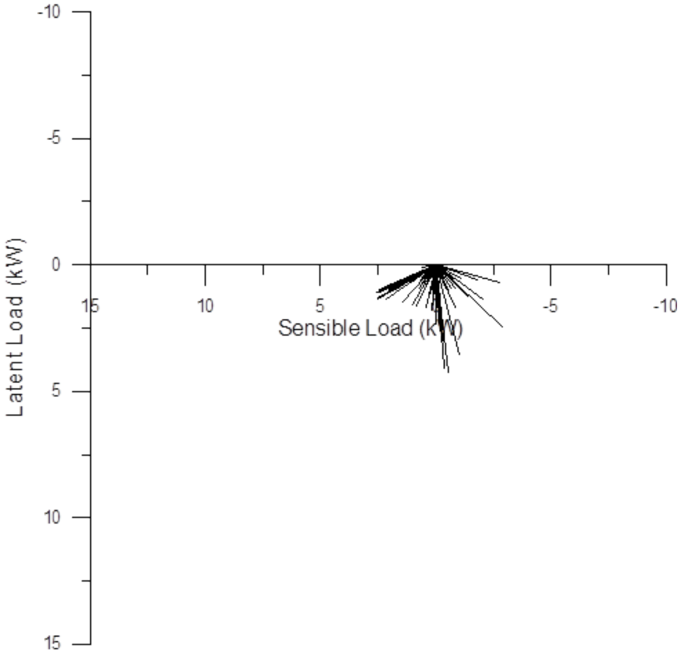


(a) Annual results

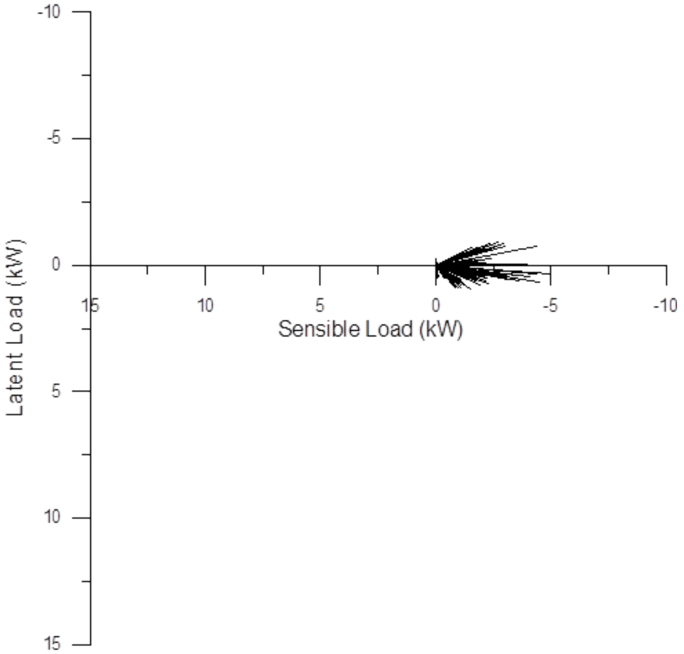


(b) Winter 1

Figure 4.6: Results from simulation of 2006 house, single point plots

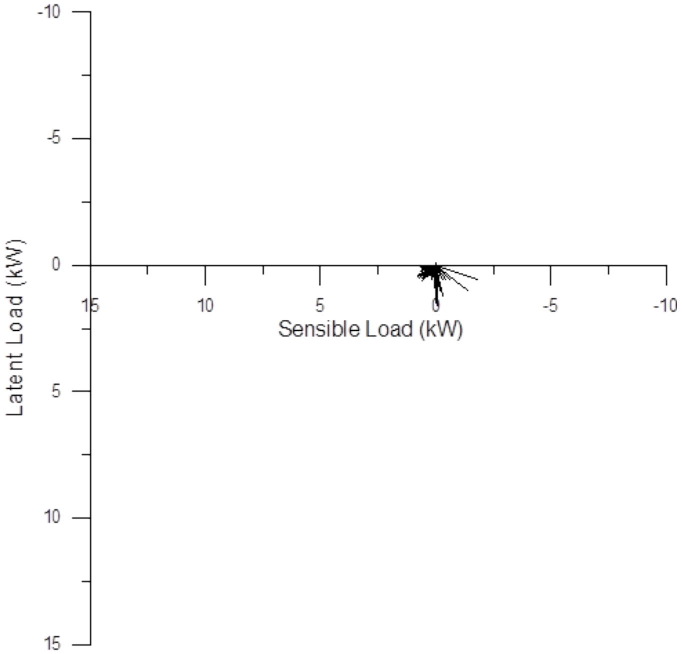


(c) Spring

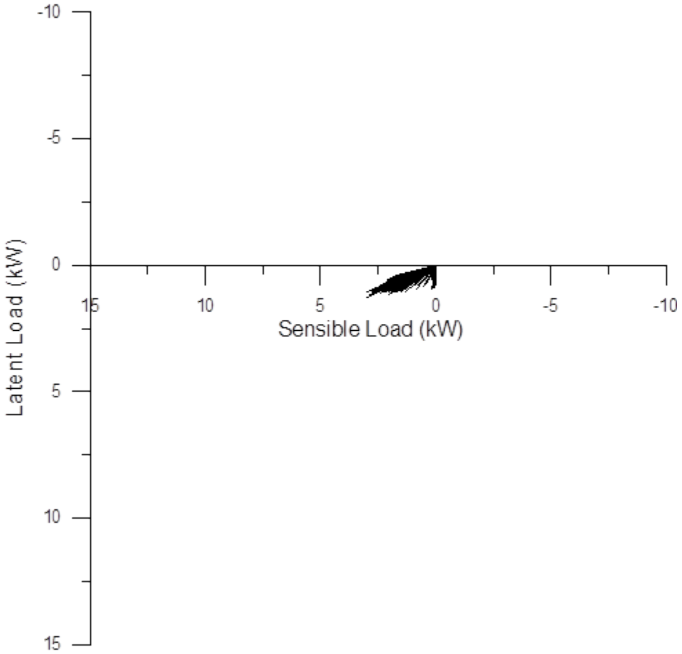


(d) Summer

Results from simulation of 2006 house, single point plots



(e) Fall



(f) Winter 2

Results from simulation of 2006 house, single point plots

The rosette for the entire year shows that there are fewer peaks for all load conditions for the 2006 house. When the typical weeks are examined, the distribution of the load lines around the condition points becomes narrower. This shows that the increased insulation and the reduced air infiltration have reduced both the magnitudes of the loads, and the variation in the loads, both over the entire year, and through the typical weeks for each season. The plots support the conclusion that the loads for this house are dominated by sensible heating and humidification, followed closely by those loads with sensible cooling.

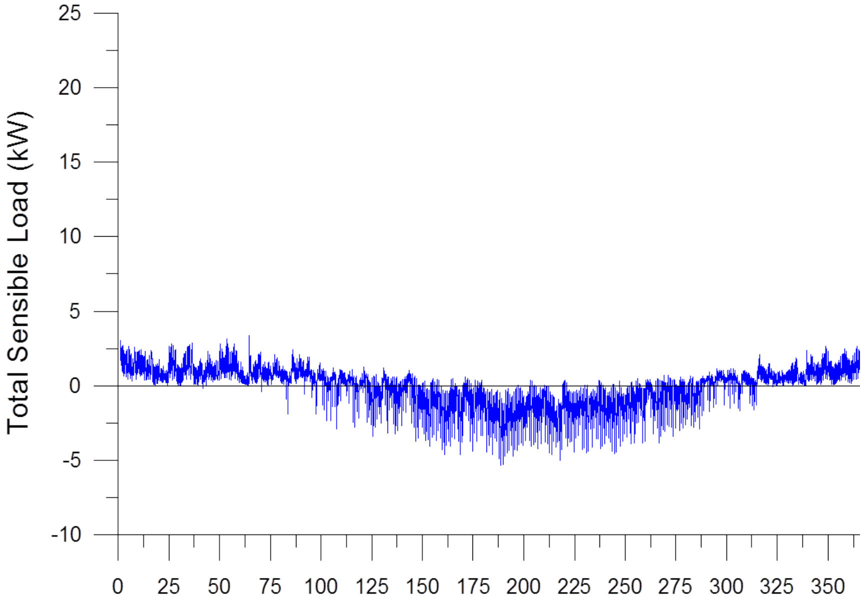
4.1.3 Super House A - Base Case for Energy Efficient House

The key parameters used in the simulation of Super House A are outlined in Table 4.8.

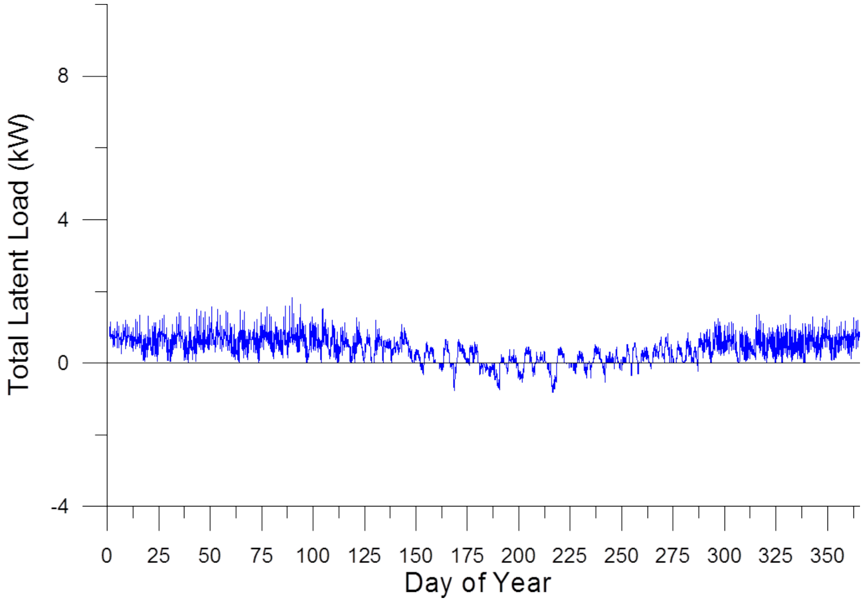
Table 4.8: Key parameters for simulation of Super House A

Parameter	**Value for Super A House**
R-value, Walls $\left(\dfrac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	40
R-value, Roof $\left(\dfrac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	60
Windows	Triple paned, argon filled, low-e coatings on surfaces 2 and 5
R-value, Floor $\left(\dfrac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	20
Number of Occupants	2 adults

Figure 4.7 shows the loads for the Super A house, showing the progression of the loads from January 1st to December 31st. The peak loads are compiled in Table 4.9, which shows that the dominant loads for the Super A house are now sensible cooling and humidification. The frequency of each possible load combination that occurs for the 2006 house are compiled in Table 4.10.



(a) Sensible heating and cooling loads



(b) Dehumidification and humidification loads

Figure 4.7: Space conditioning loads at each timestep for Super House A

Table 4.9: Peak loads for the entire year for the Super House A

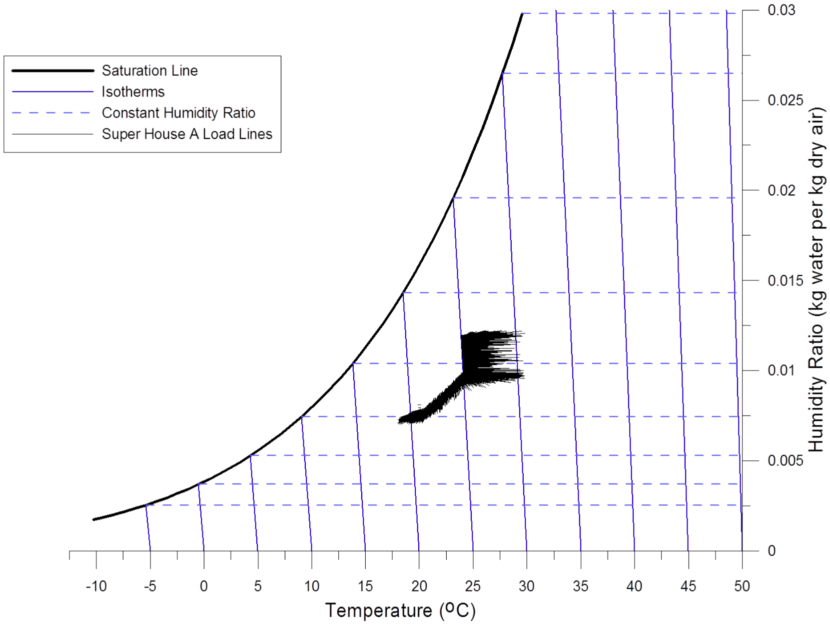
Load condition	**Maximum Value (kW)**	**Total kWhr**
Sensible heating	1.6	913.40
Sensible cooling	4.73	5295.83
Dehumidification	0.81	182.84
Humidification	1.74	3738.84

Table 4.10: Frequency of possible load conditions for Super House A

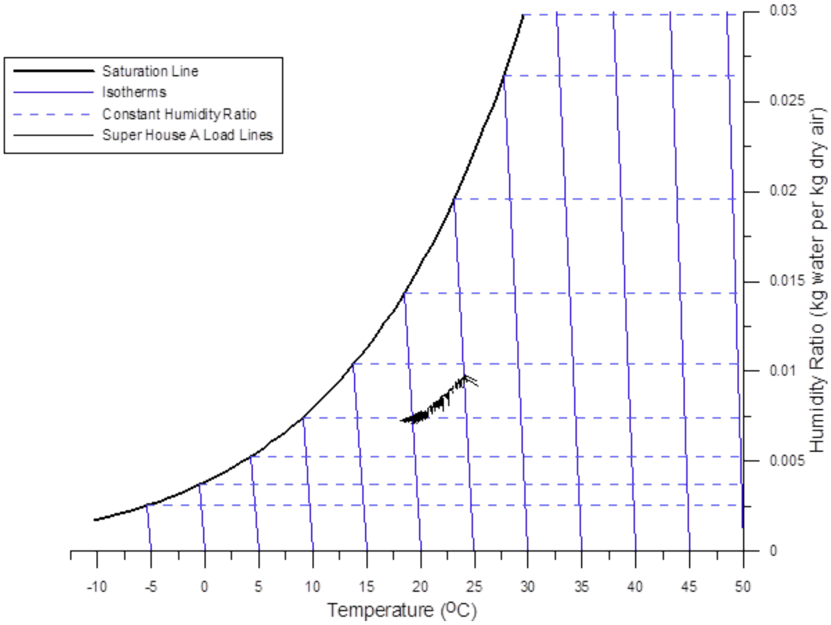
Load Condition	**Hours**	**Days**
Sensible Heating Only	0	0.0
Sensible Heating and Humidification	1826	76.08
Sensible Heating and Dehumidification	0	0.0
Sensible Cooling Only	842	35.08
Sensible Cooling and Humidification	3129	130.38
Sensible Cooling and Dehumidification	785	32.71
Humidification Only	2163	90.13
Dehumidification Only	0	0.0
All Sensible Heating	1826	76.08
All Sensible Cooling	4756	198.17
All Humidification	7118	296.58
All Dehumidification	785	32.71

Table 4.10 shows that the loads for Super House A are dominated by sensible cooling (4756 hours) and humidification (7118 hours). Sensible cooling and humidification is the most common load condition for this house, occurring 3129 times during the year. The frequency analysis only considers how often each load condition occurs, it does not take into account the magnitude of each load.

The psychrometric charts with the results from the Super House A are in Figure 4.8. The results for the entire year are shown on Figure 4.8a, and Figures 4.8b through 4.8f. Similarly, the single point plots are presented in Figure 4.9.

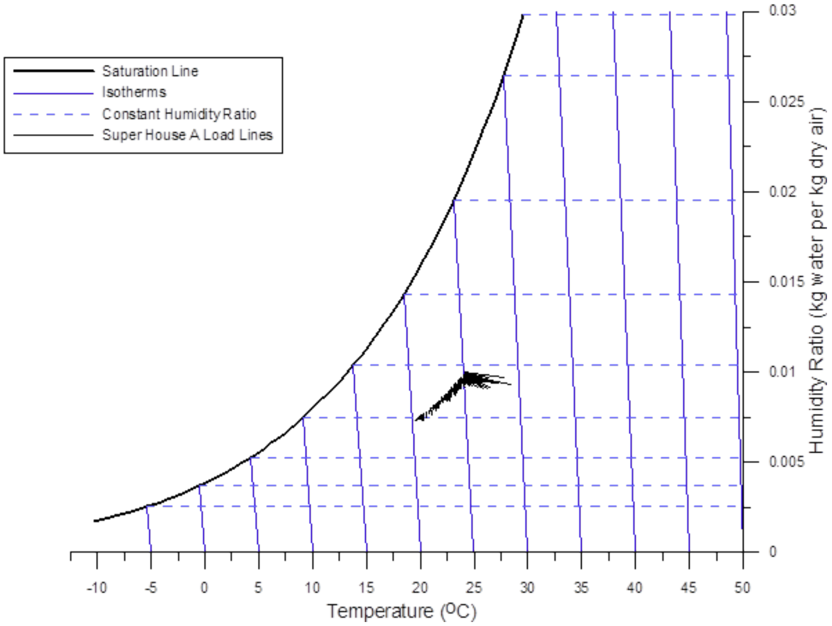


(a) Entire year

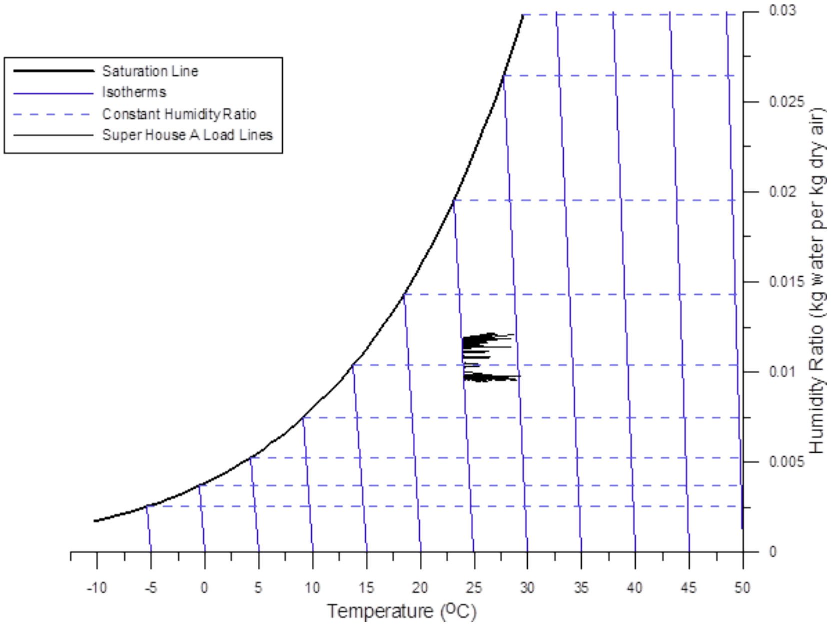


(b) Winter 1

Figure 4.8: Results from simulation of Super House A

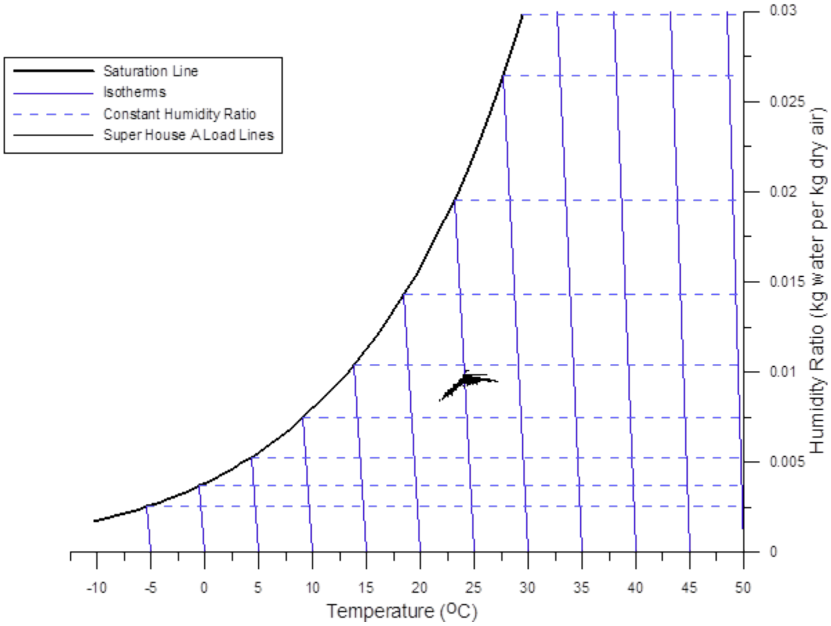


(c) Spring

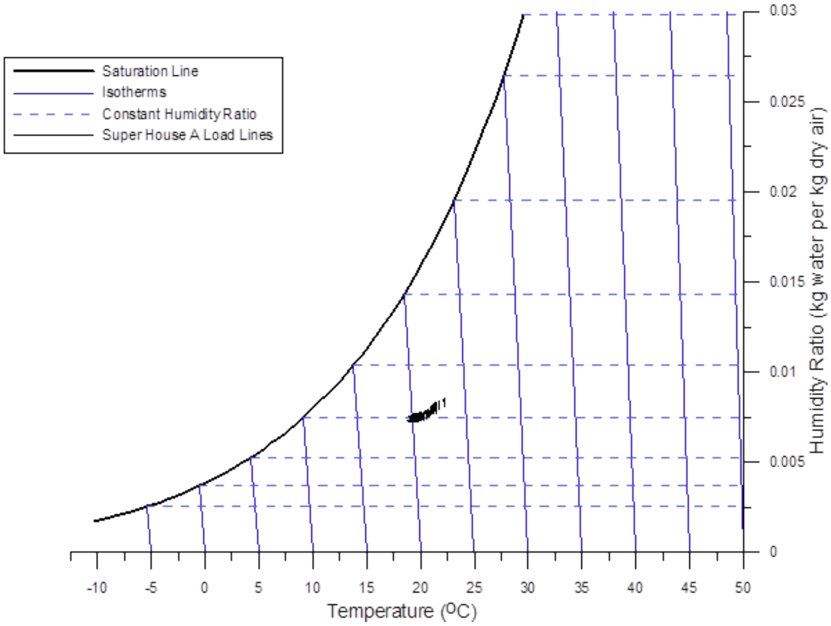


(d) Summer

Results from simulation of Super House A

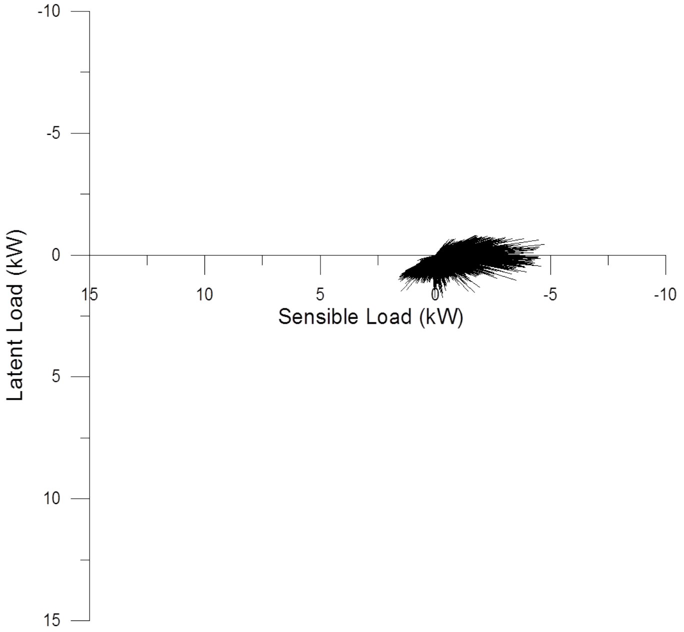


(e) Fall

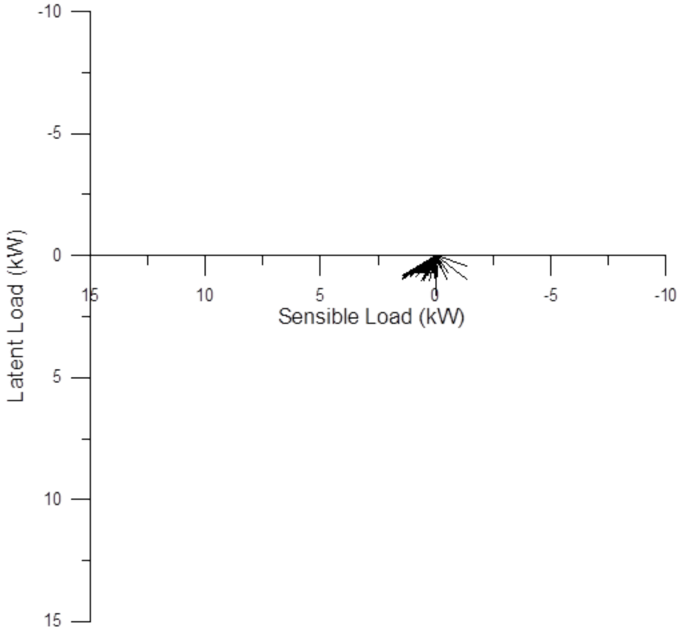


(f) Winter 2

Results from simulation of Super House A

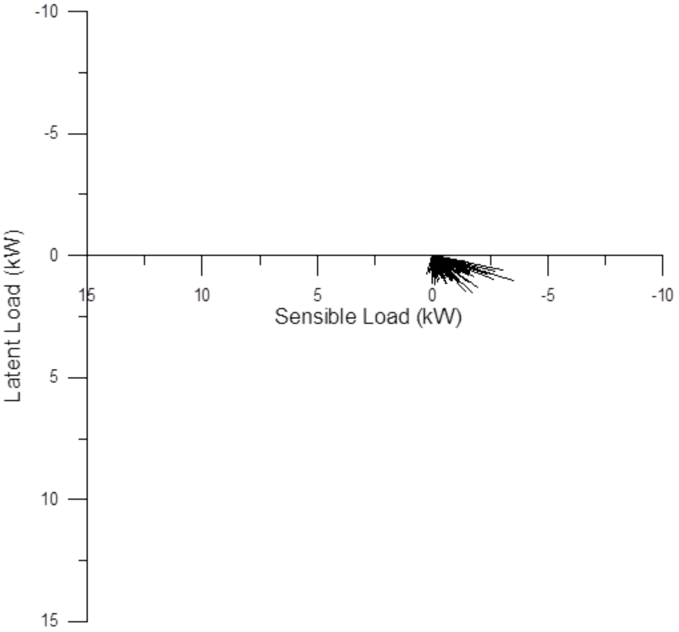


(a) Annual results

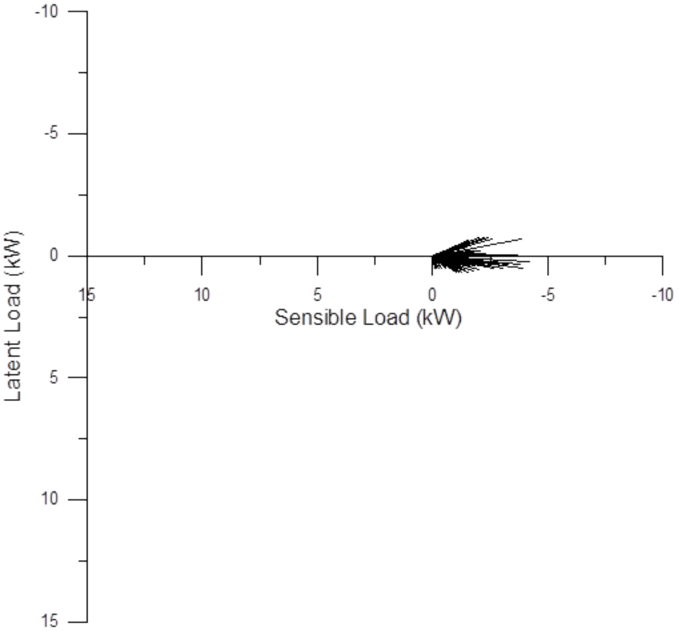


(b) Winter 1

Figure 4.9: Results from simulation of Super House A, single point plots

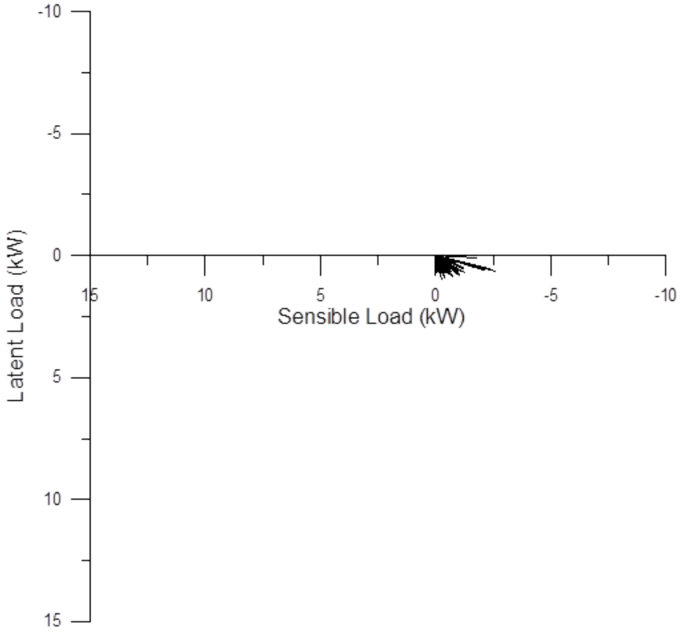


(c) Spring

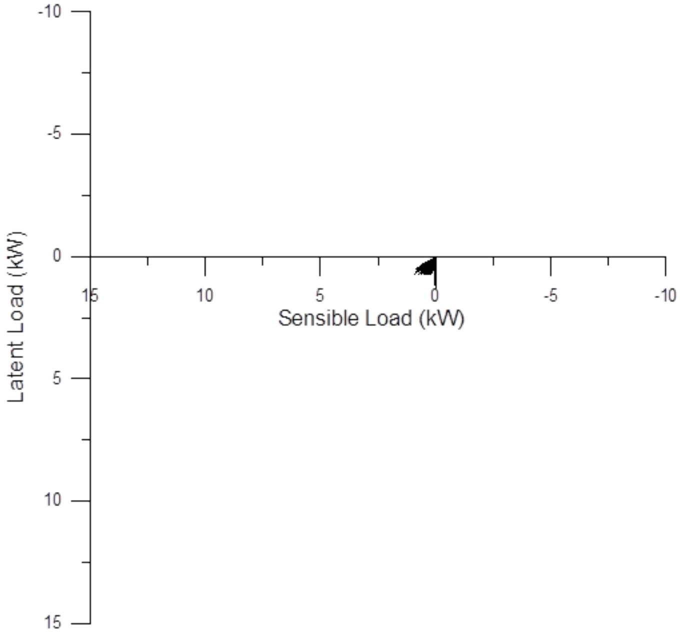


(d) Summer

Results from simulation of Super House A, single point plots



(e) Fall



(f) Winter 2

Results from simulation of Super House A, single point plots

Examining the plots for this house, there are few peaks and the loads are much smaller. Sensible cooling is much more frequent for this house, even though the magnitude of these cooling loads may be very small. Figure 4.7 shows that the sensible cooling season is much longer than the sensible heating season for this house, supporting the conclusion that the equipment loads in this house are dominated by sensible cooling and humidification.

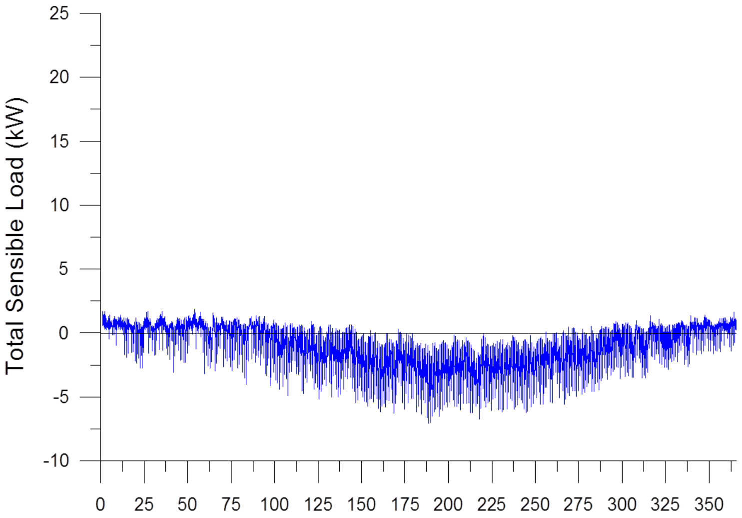
4.1.4 Super House B - Energy Efficient House, Increased Occupancy

Key parameters used in the simulation of Super House B are compiled in Table 4.11. This house uses the same construction as Super House A, but the occupancy is increased from two to four, and the occupancy schedules have been updated accordingly.

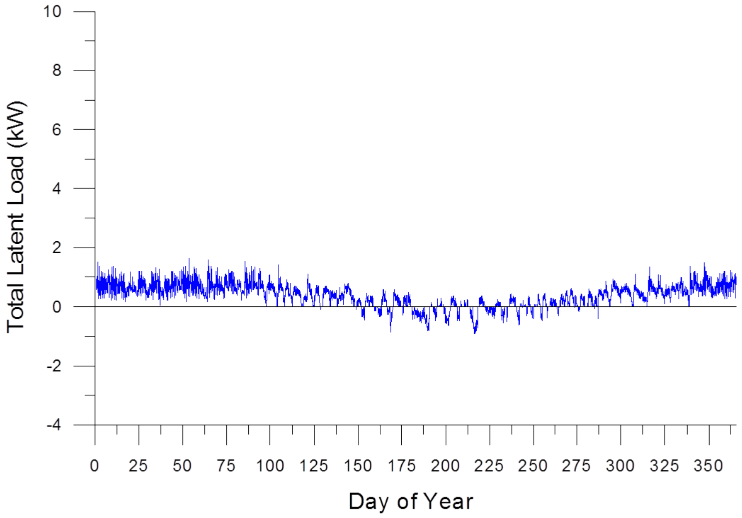
Table 4.11: Key parameters for simulation of Super House B

Parameter	**Value for Super House B**
R-value, Walls $\left(\frac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	40
R-value, Roof $\left(\frac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	60
Windows	Triple paned, argon filled, low-e coatings on surfaces 2 and 5
R-value, Floor $\left(\frac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	20
Number of Occupants	4 adults

Figure 4.10 shows the loads for the Super B house, showing the loads from January 1st to December 31st. The peak loads are compiled in Table 4.12, which show that the dominant loads for the Super B house are sensible cooling and humidification. The frequency of each possible load combination that occurs for the 2006 house are compiled in Table 4.13.



(a) Sensible heating and cooling loads



(b) Dehumidification and humidification loads

Figure 4.10: Space conditioning loads at each timestep for Super B House

Table 4.12: Peak loads for the entire year for the Super B House

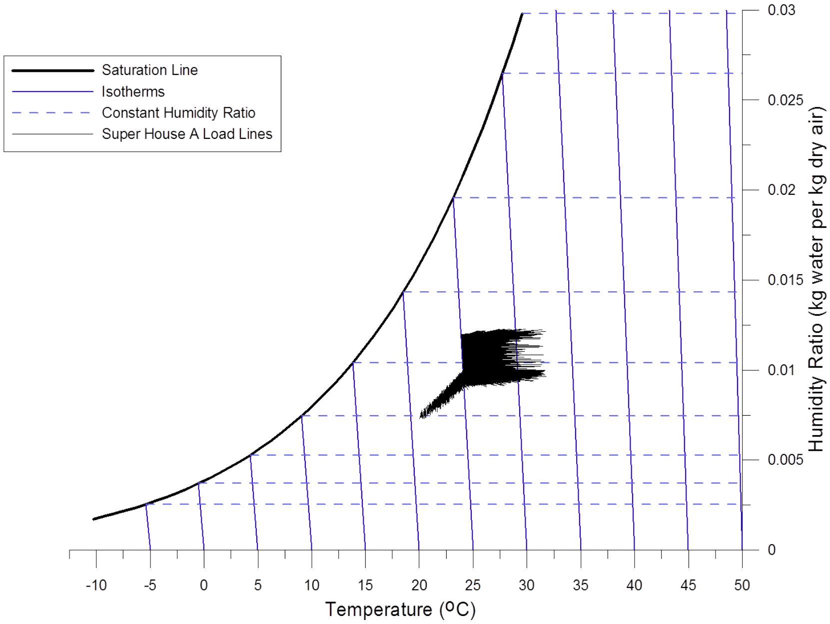
Load condition	**Maximum Value (kW)**	**Total kWhr**
Sensible heating	0.15	0.62
Sensible cooling	6.3	13100.65
Dehumidification	0.92	285.18
Humidification	1.71	3740.71

Table 4.13: Frequency of possible load conditions for Super B House

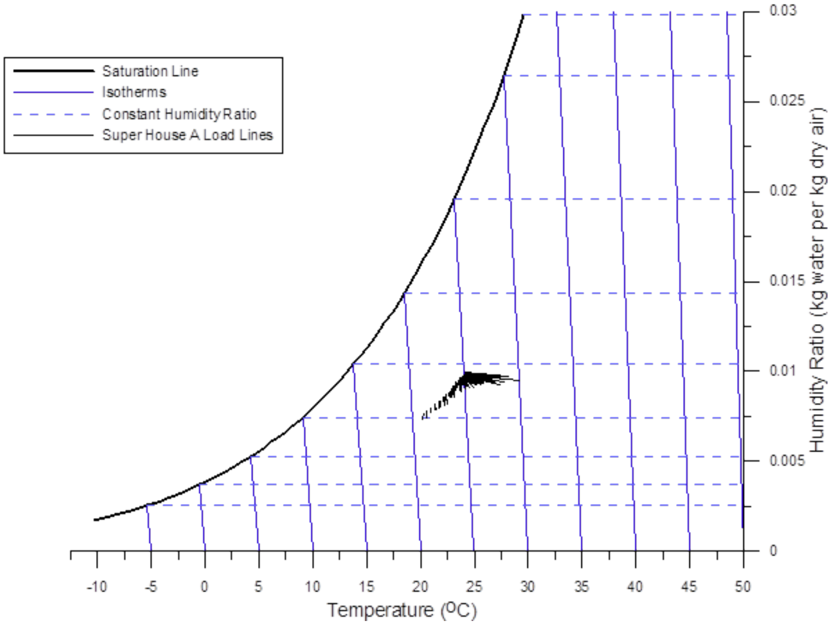
Load Condition	**Hours**	**Days**
Sensible Heating Only	0	0.0
Sensible Heating and Humidification	15	0.63
Sensible Heating and Dehumidification	0	0.0
Sensible Cooling Only	1058	44.08
Sensible Cooling and Humidification	5661	235.88
Sensible Cooling and Dehumidification	1024	42.67
Humidification Only	1002	41.75
Dehumidification Only	0	0.0
All Sensible Heating	15	0.63
All Sensible Cooling	7743	322.63
All Humidification	6678	278.25
All Dehumidification	1024	42.67

Table 4.13 shows that the loads for the Super B house are dominated by sensible cooling (7743 hours) and humidification (6678 hours). Sensible cooling and humidification is the most common combination of load conditions for this house, occurring 5661 times during the year.

Psychrometric charts showing the results from Super House B in Figure 4.11. The results for the entire year are shown on Figure 4.11a, and Figures 4.11b through 4.11f. Similarly, the single point plots are presented in Figure 4.12.

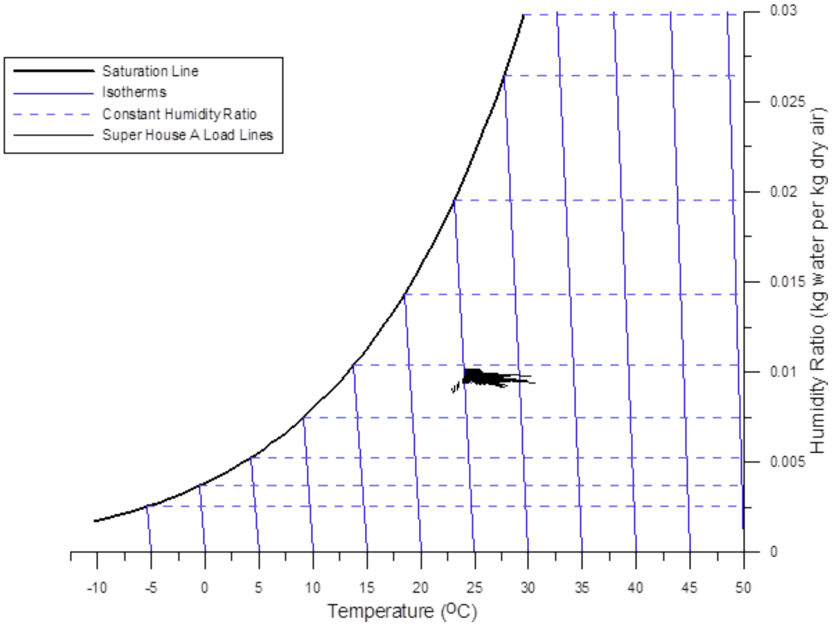


(a) Entire year

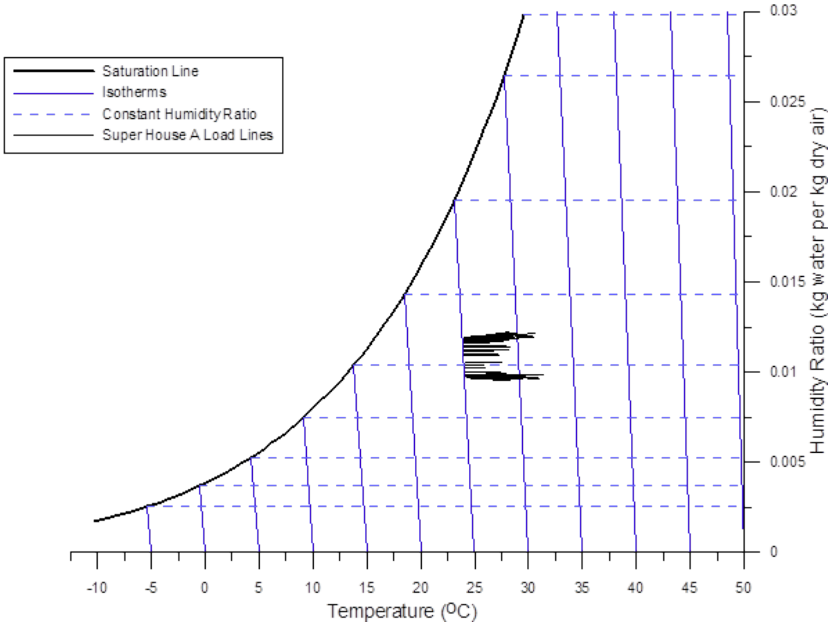


(b) Winter 1

Figure 4.11: Results from simulation of Super B house

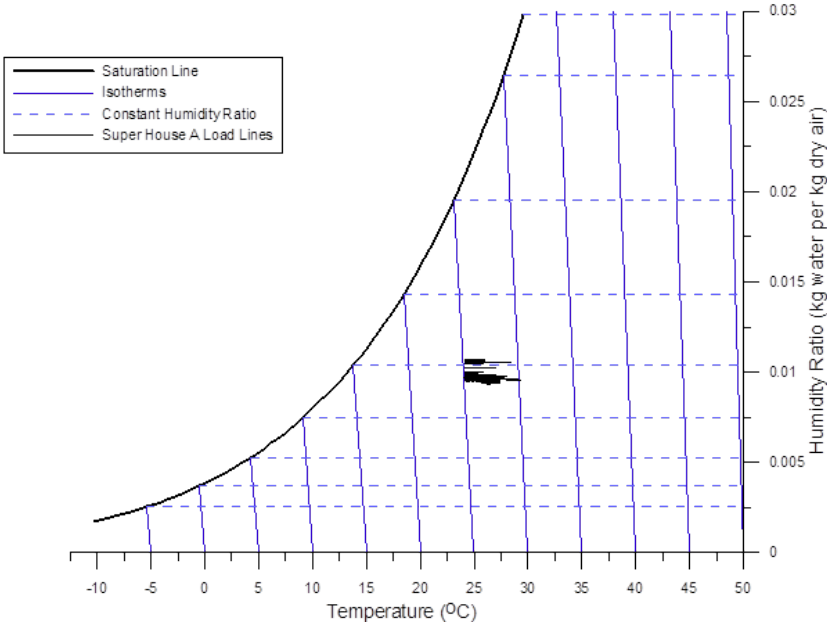


(c) Spring

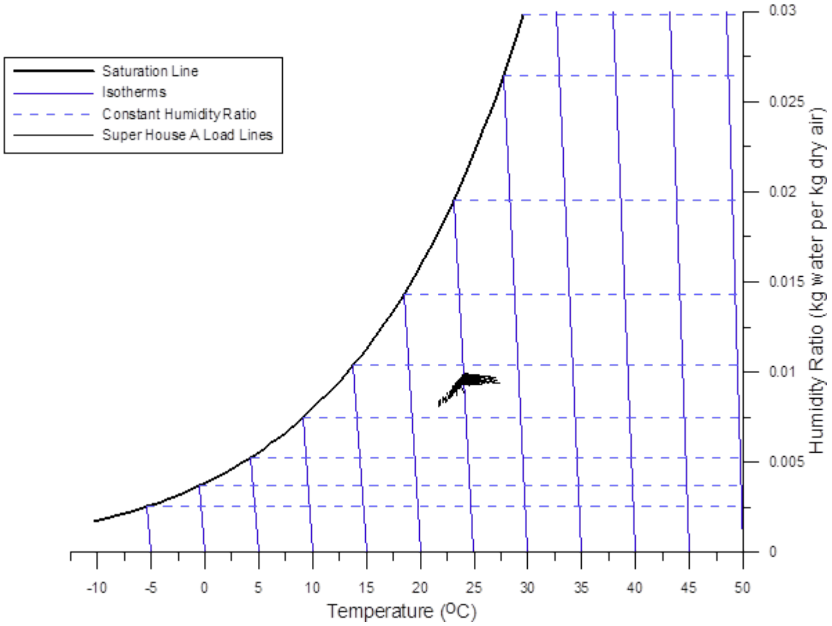


(d) Summer

Results from simulation of Super B house

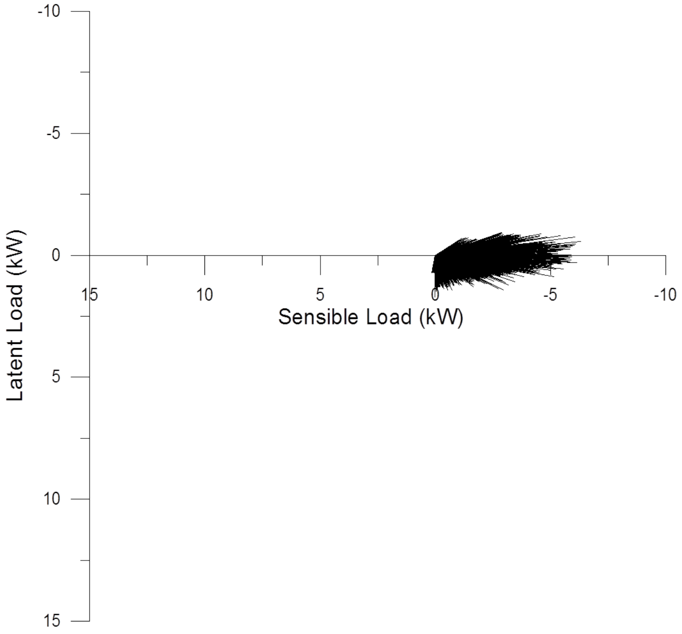


(e) Fall

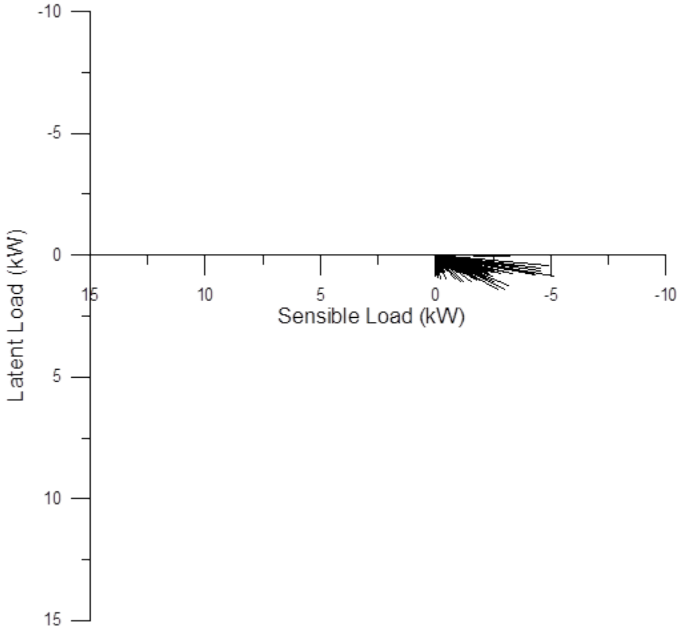


(f) Winter 2

Results from simulation of Super B house

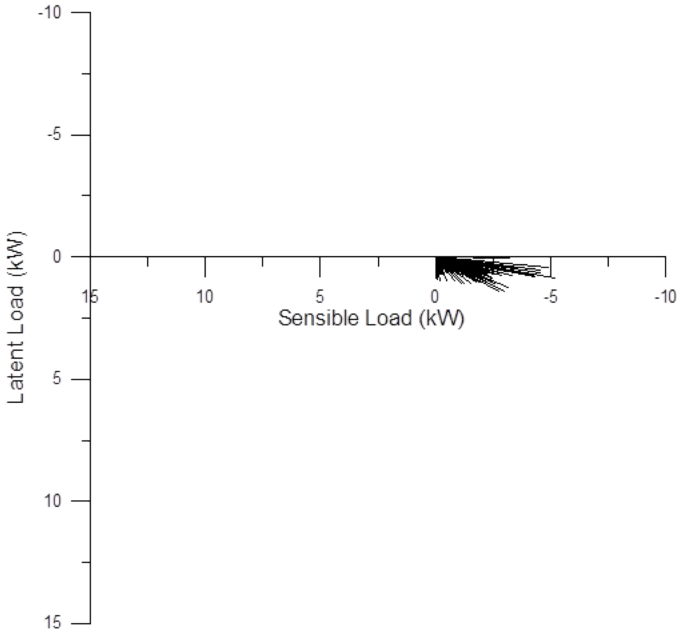


(a) Annual results

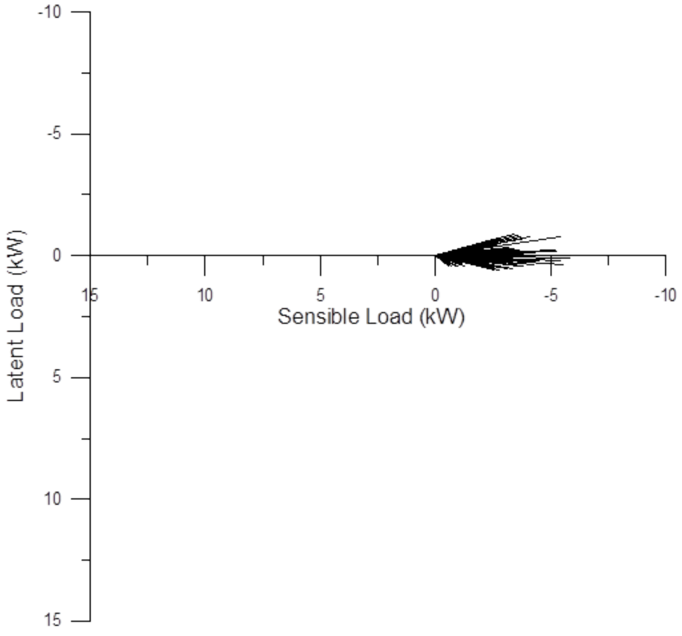


(b) Winter 1

Figure 4.12: Results from simulation of Super B house, single point plots

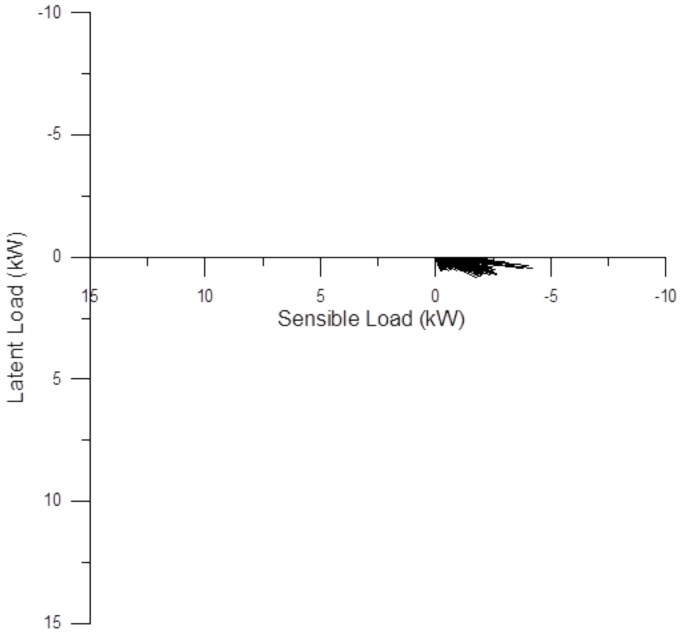


(c) Spring

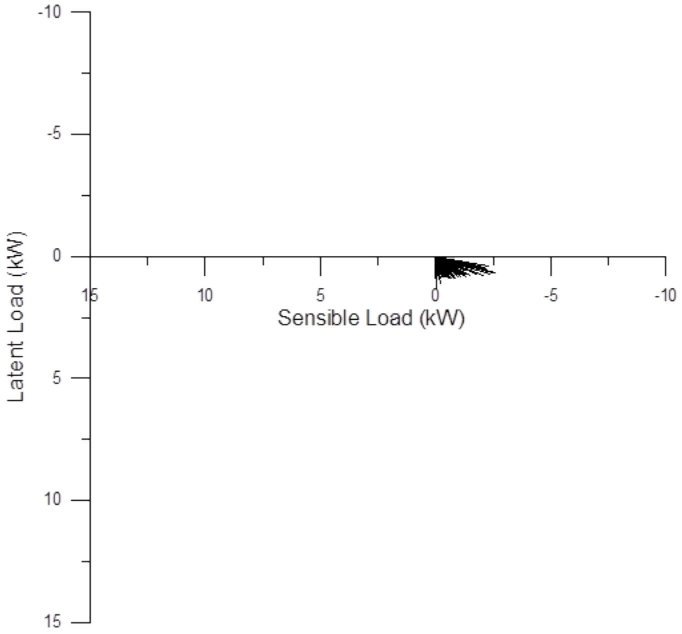


(d) Summer

Results from simulation of Super B house, single point plots



(e) Fall



(f) Winter 2

Results from simulation of Super B house, single point plots

Doubling the number of occupants in a house that is extremely insulated has eliminated most of the sensible heating loads, and increased the number and magnitude of the sensible cooling loads. This house has large internal sensible gains and very small losses through the envelope. The plots for this house support the conclusion that the equipment loads for this house are dominated by humidification and sensible cooling.

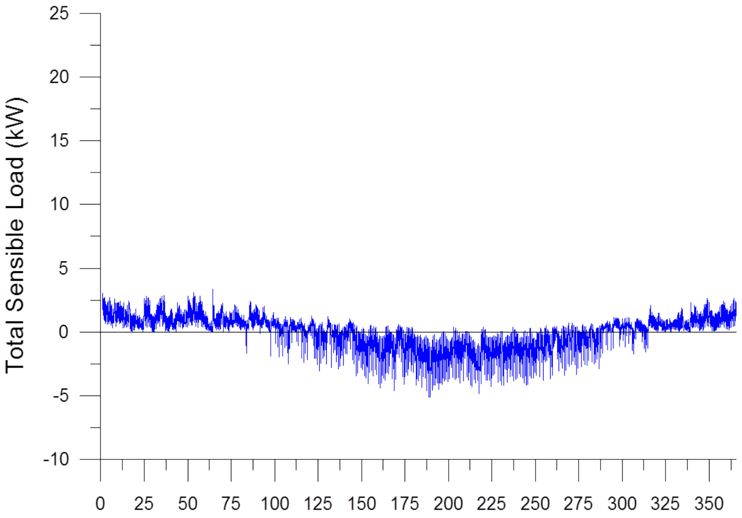
4.1.5 Super House C - Energy Efficient House with Dynamic Shading

Key parameters used in the simulation of Super House C are compiled in Table 4.14. This house is the same as Super House A with the addition of control loops to adjust the shading to account for insolation levels. Shading is provided by a 1 inch light coloured Venetian blind located on the interior side of the window.

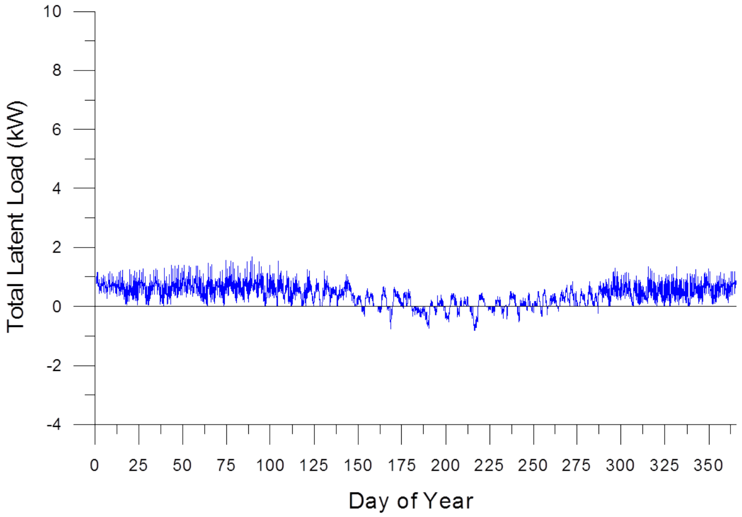
Table 4.14: Key parameters for simulation of Super House C

Parameter	**Value for Super House C**
R-value, Walls $\left(\dfrac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	40
R-value, Roof $\left(\dfrac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	60
Windows	Triple paned, argon filled, low-e coatings on surfaces 2 and 5.
R-value, Floor $\left(\dfrac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	20
Number of Occupants	2 adults

Figure 4.13 shows the loads for the Super C house, showing the progression of the loads from January 1st to December 31st. The peak loads are compiled in Table 4.15, which show that the dominant loads for the Super C house are sensible cooling and humidification. The frequency of each possible load combination that occurs for Super House C is presented in Table 4.16.



(a) Sensible heating and cooling loads



(b) Dehumidification and humidification loads

Figure 4.13: Space conditioning loads at each timestep for Super C House

Table 4.15: Peak loads for the entire year for the Super C House

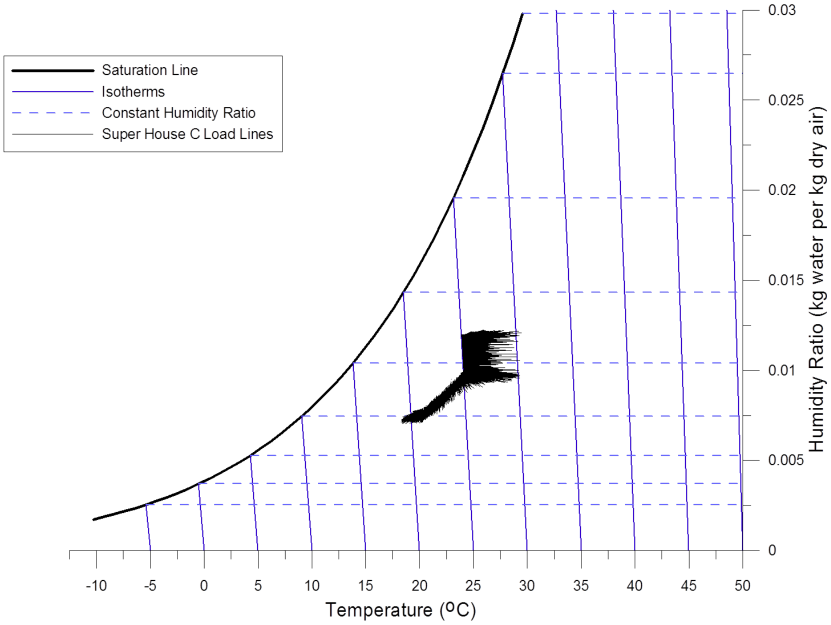
Load condition	**Maximum Value (kW)**	**Total kWhr**
Sensible heating	1.61	949.41
Sensible cooling	4.49	4967.37
Dehumidification	0.81	182.84
Humidification	1.81	3715.41

Table 4.16: Frequency of possible load conditions for Super C House

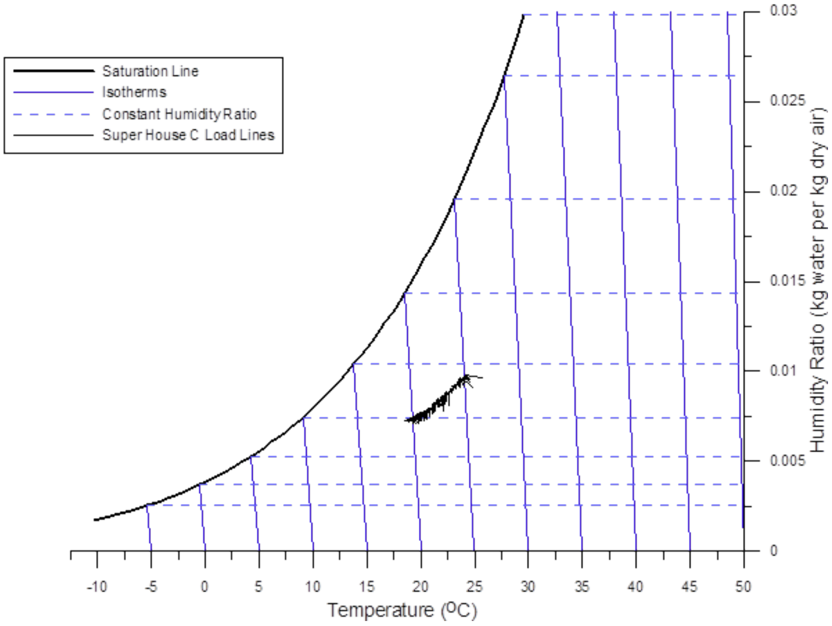
Load Condition	**Hours**	**Days**
Sensible Heating Only	0	0.0
Sensible Heating and Humidification	1911	79.63
Sensible Heating and Dehumidification	0	0.0
Sensible Cooling Only	842	35.08
Sensible Cooling and Humidification	3032	126.33
Sensible Cooling and Dehumidification	785	32.71
Humidification Only	2176	90.67
Dehumidification Only	0	0.0
All Sensible Heating	1911	79.63
All Sensible Cooling	4659	194.13
All Humidification	7119	296.63
All Dehumidification	785	32.71

Table 4.16 shows that the loads for the Super C house are dominated by sensible cooling (4659 hours) and humidification (7119 hours). Sensible cooling and humidification is the most common combination of load conditions for this house. This load combination occurred 3032 times during the year.

The results for the Super C house are plotted on the psychrometric chart in Figure 4.14. The results for the entire year are shown on Figure 4.14a, and Figures 4.14b through 4.14f. Single point plots for this simulation are presented in Figure 4.15.

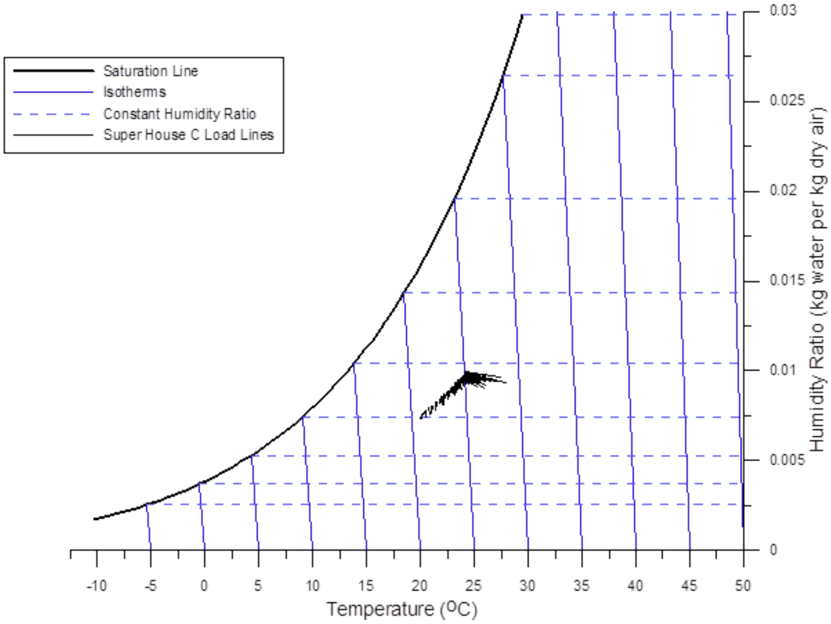


(a) Entire year

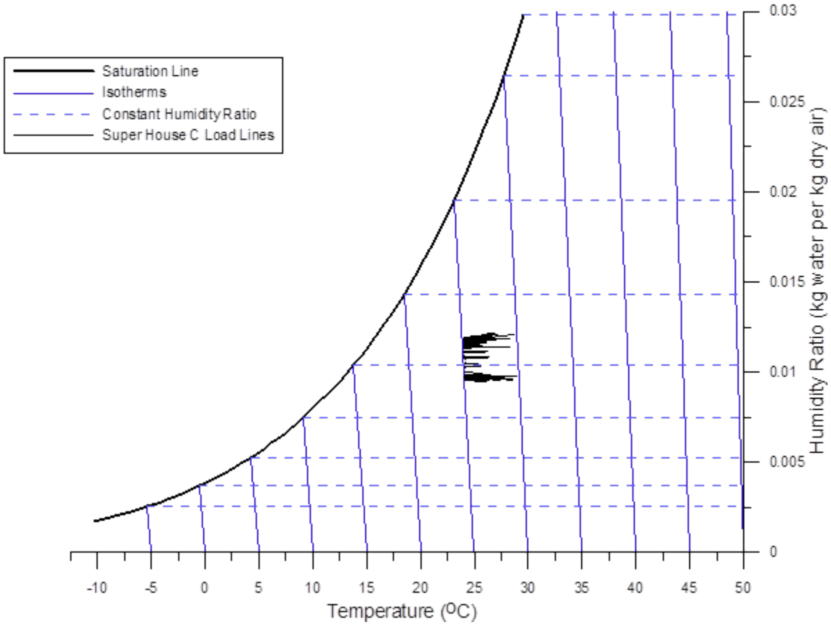


(b) Winter 1

Figure 4.14: Results from simulation of Super C house

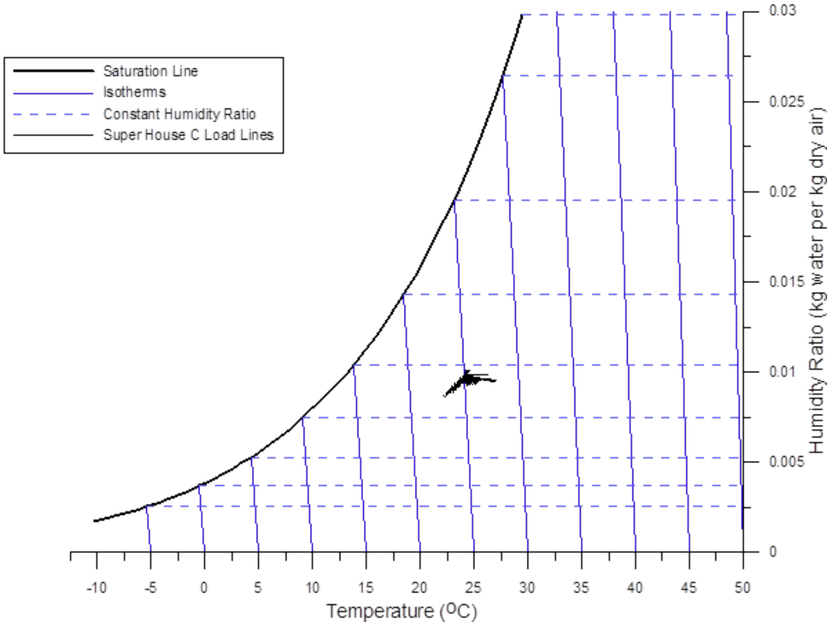


(c) Spring

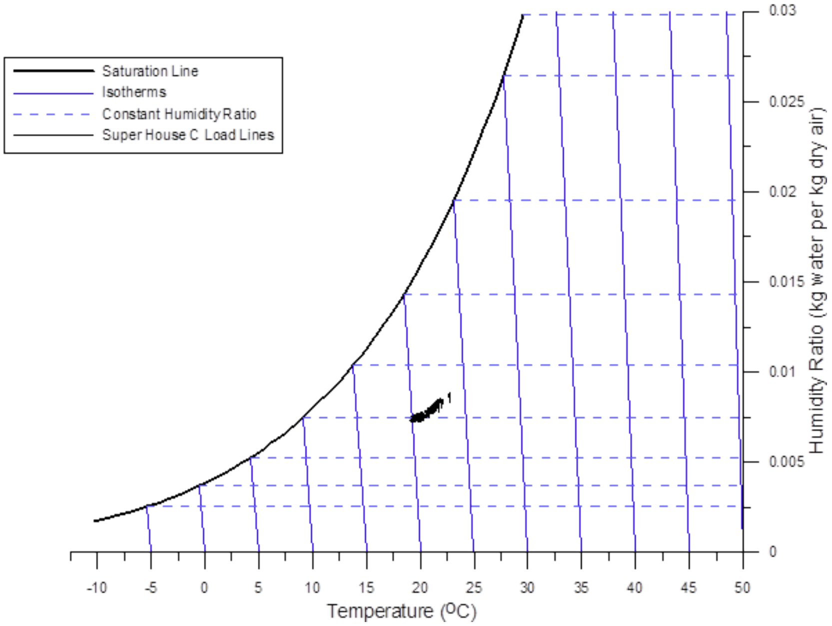


(d) Summer

Results from simulation of Super C house

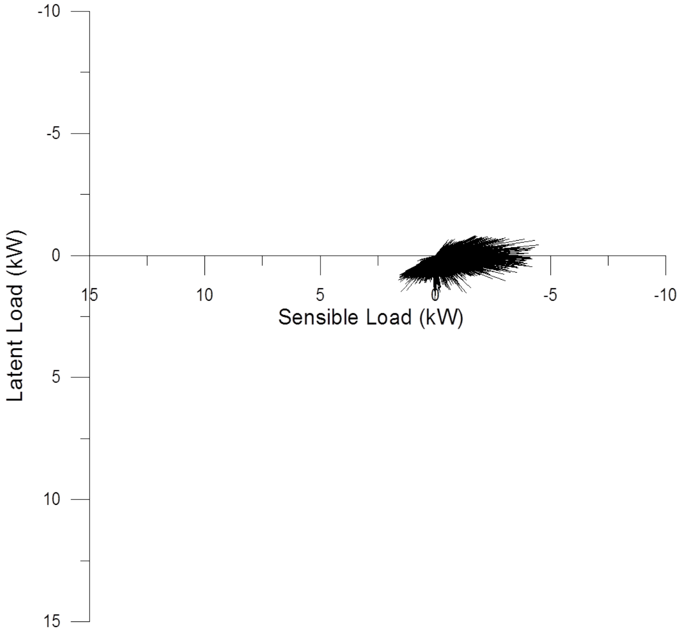


(e) Fall

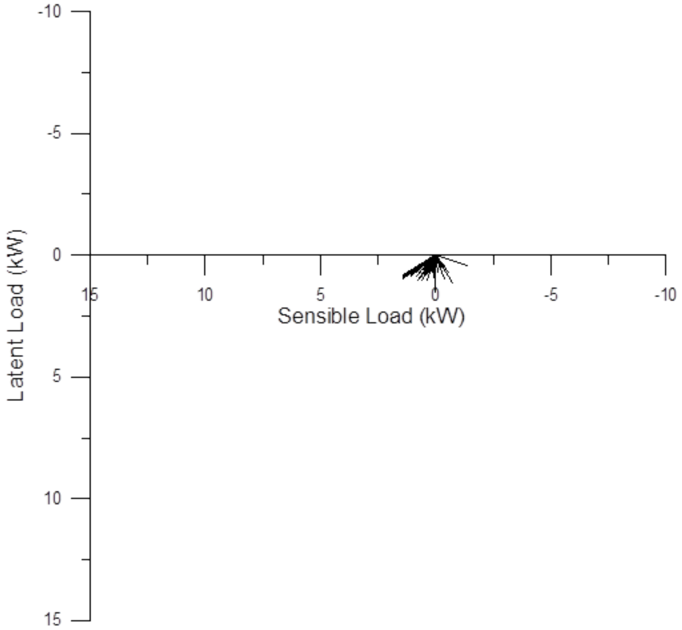


(f) Winter 2

Results from simulation of Super C house

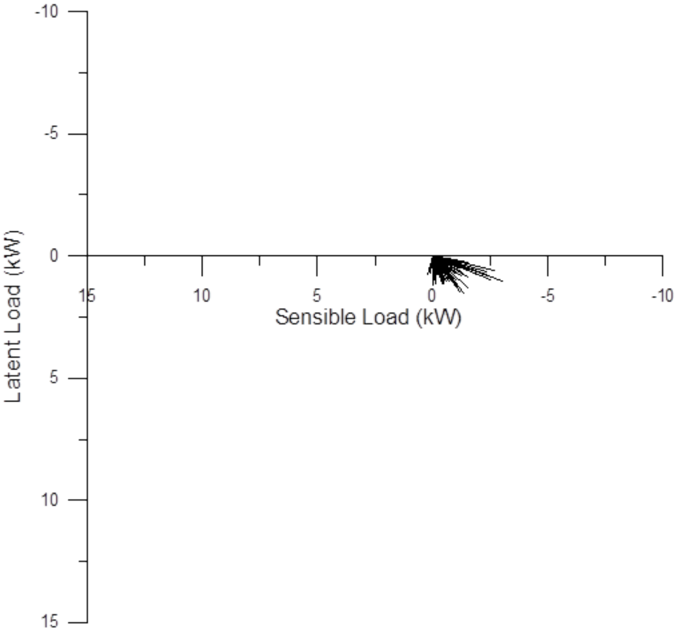


(a) Annual results

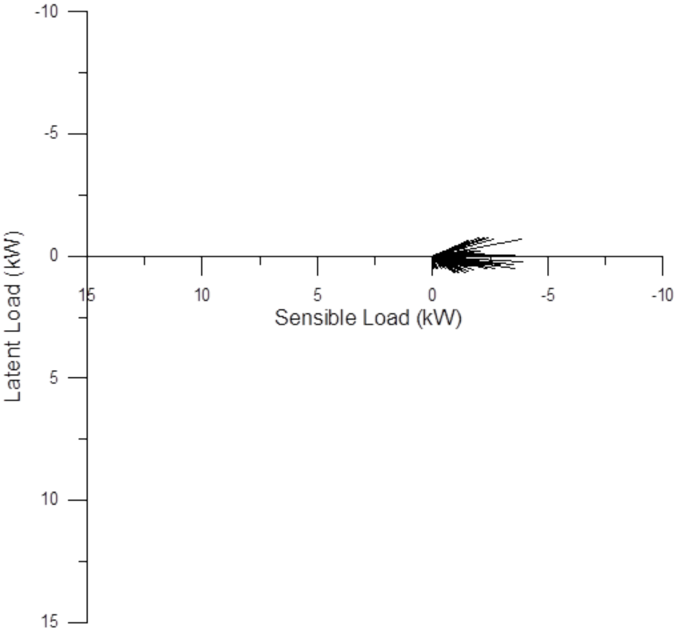


(b) Winter 1

Figure 4.15: Results from simulation of Super C house, single point plots

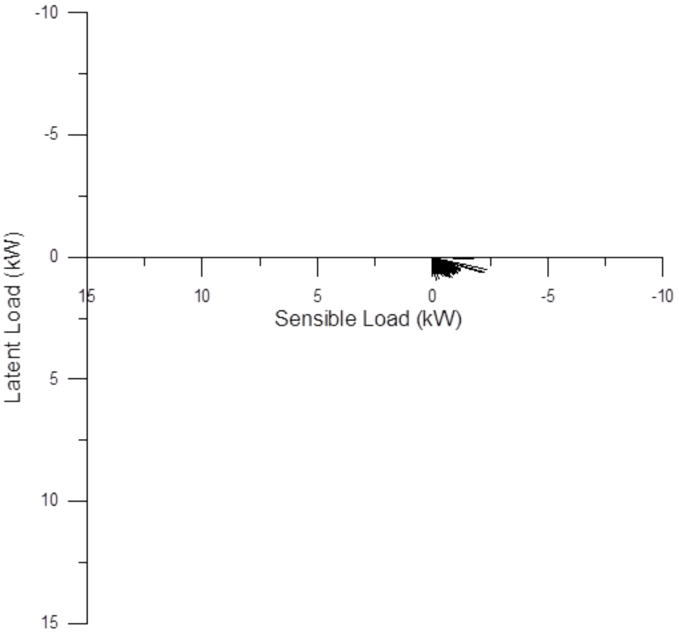


(c) Spring

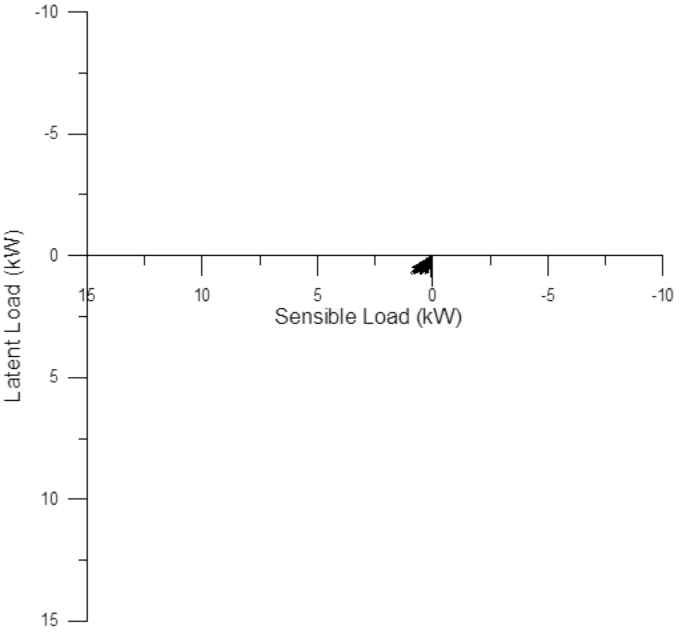


(d) Summer

Results from simulation of Super C house, single point plots



(e) Fall



(f) Winter 2

Results from simulation of Super C house, single point plots

The simulation for Super House C shows small heating loads, and relatively large cooling loads. Almost no dehumidification loads are present in this house. Based on a brief examination of frequency analysis of this house, the addition of the dynamic shading control loops only results in small changes to the equipment loads. These changes will be examined in greater detail later in this chapter.

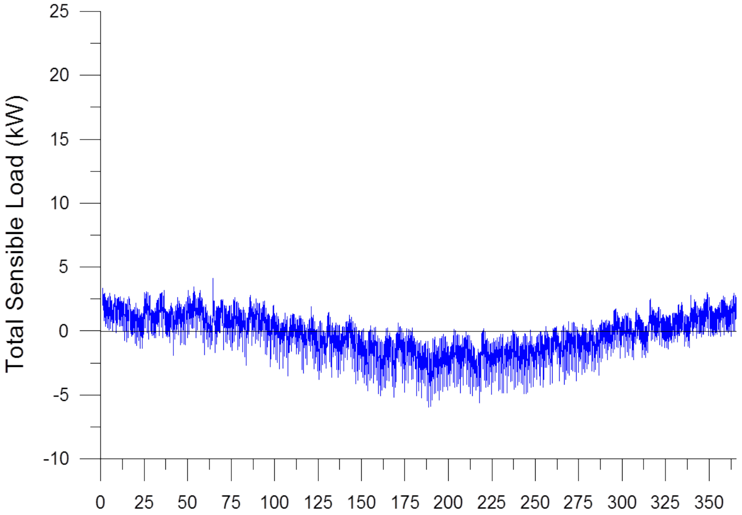
4.1.6 Super House D - Energy Efficient House with Revised Control Scheme

Key parameters used in the simulation of Super House D are compiled in Table 4.17. This house is the same as Super House A, but the HVAC control scheme has been revised to have a single setpoint of 21 degrees Celcius and 55% relative humidity.

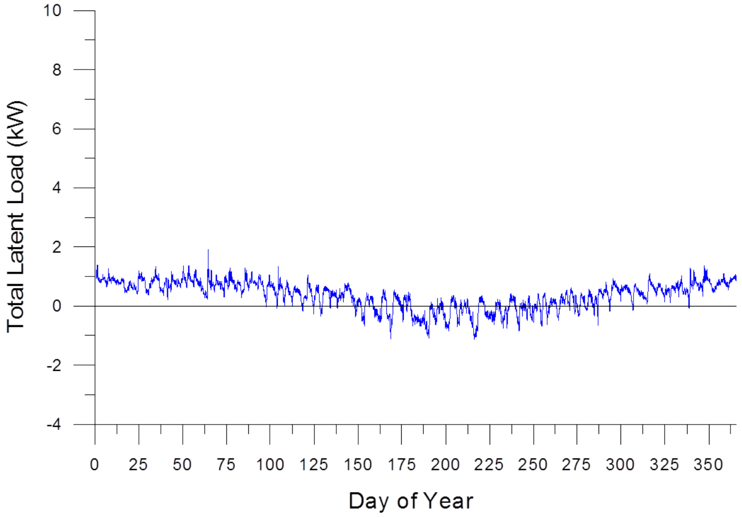
Table 4.17: Key parameters for simulation of Super House D

Parameter	**Value for Super House D**
R-value, Walls $\left(\frac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	40
R-value, Roof $\left(\frac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	60
Windows	Triple paned, argon filled, low-e coatings on surfaces 2 and 5
R-value, Floor $\left(\frac{ft^2 * {}^\circ\mathrm{F} * hr}{BTU}\right)$	20
Number of Occupants	2 adults

Figure 4.16 shows the loads for the Super House D, showing the progression of the loads from January 1st to December 31st. The peak loads are compiled in Table 4.18, which show that the dominant loads for the Super B house are sensible cooling and humidification. The frequency of each possible load combination that occurs for Super House D are compiled in Table 4.19.



(a) Sensible heating and cooling loads



(b) Dehumidification and humidification loads

Figure 4.16: Space conditioning loads at each timestep for Super House D

Table 4.18: Peak loads for the entire year for the Super House D

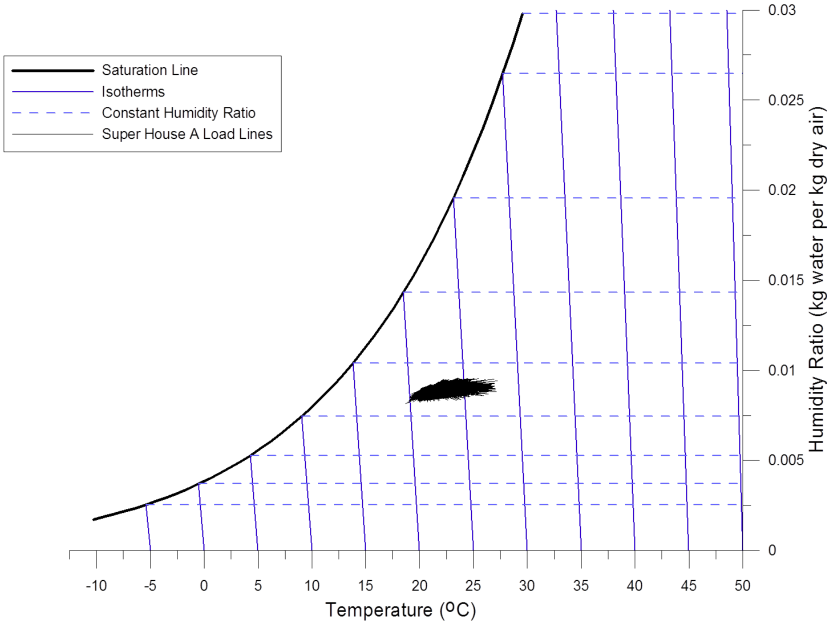
Load condition	**Maximum Value (kW)**	**Total kWhr**
Sensible heating	2	1551.94
Sensible cooling	4.96	6957.67
Dehumidification	1.13	633.88
Humidification	1.92	3822.3

Table 4.19: Frequency of possible load conditions for Super House D

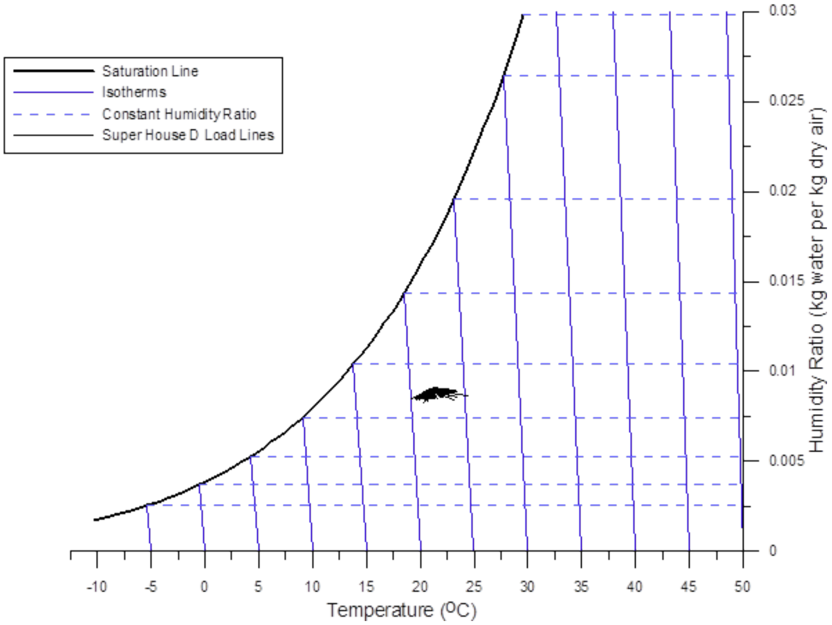
Load Condition	**Hours**	**Days**
Sensible Heating Only	0	0.0
Sensible Heating and Humidification	2720	113.33
Sensible Heating and Dehumidification	0	0.0
Sensible Cooling Only	47	1.96
Sensible Cooling and Humidification	4085	170.21
Sensible Cooling and Dehumidification	1880	78.33
Humidification Only	28	1.17
Dehumidification Only	0	0.0
All Sensible Heating	2770	113.33
All Sensible Cooling	6012	250.50
All Humidification	6833	284.71
All Dehumidification	1880	78.33

Table 4.19 shows that the loads for Super House D are dominated by sensible cooling (6012 hours) and humidification (6883 hours). Sensible cooling and humidification is the most common load condition for this house, occurring 4085 times during the year.

The results for Super House D are plotted on the psychrometric chart in Figure 4.17. The results for the entire year are shown on Figure 4.17a, and Figures 4.17b through 4.17f. Single point plots for Super House D are presented in Figure 4.18.

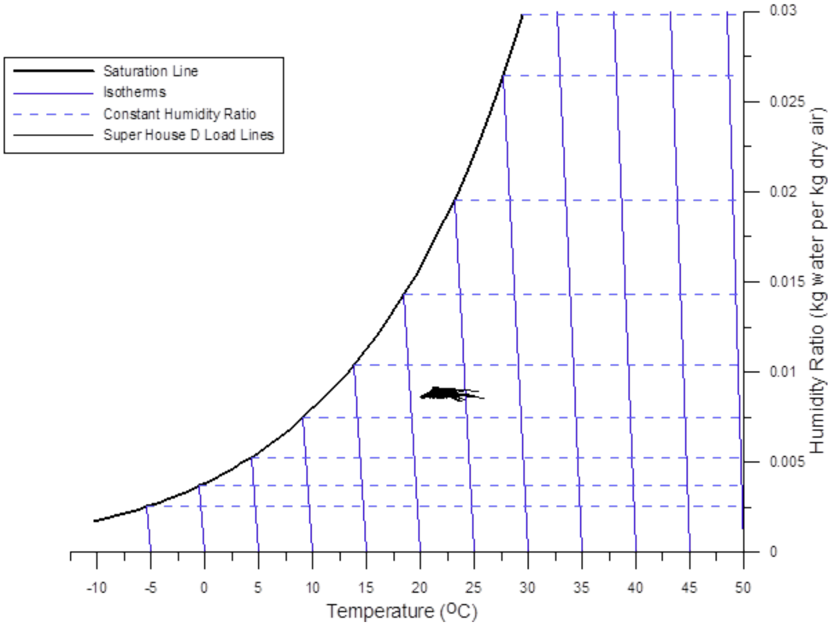


(a) Entire year

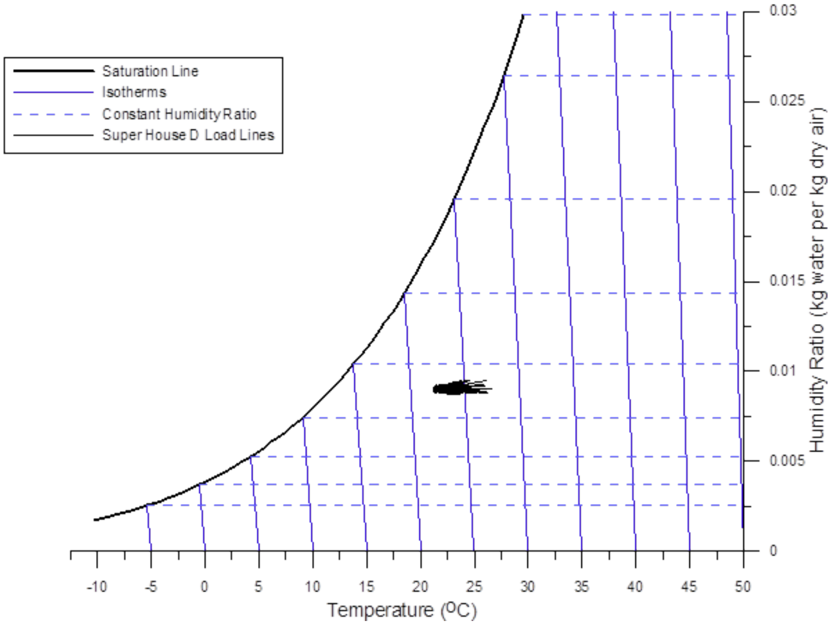


(b) Winter 1

Figure 4.17: Results from simulation of Super House D

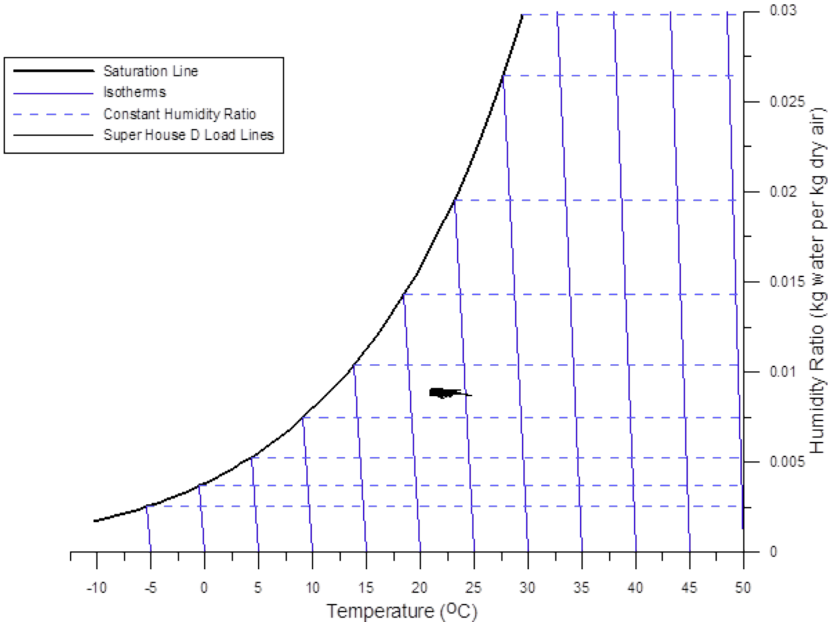


(c) Spring

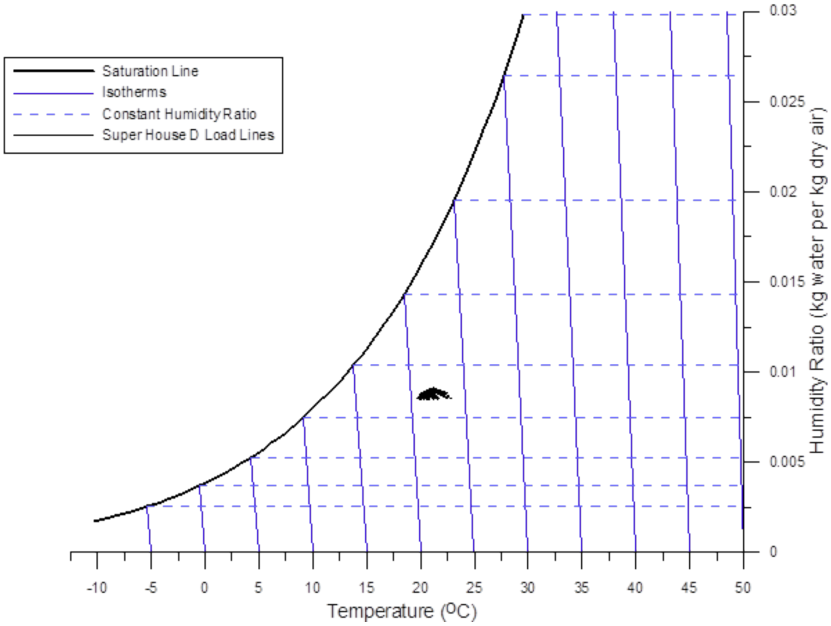


(d) Summer

Results from simulation of Super House D

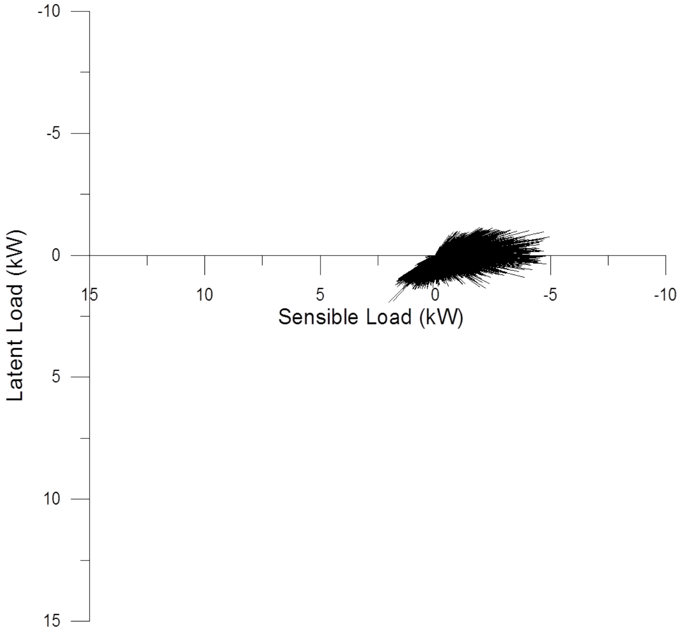


(e) Fall

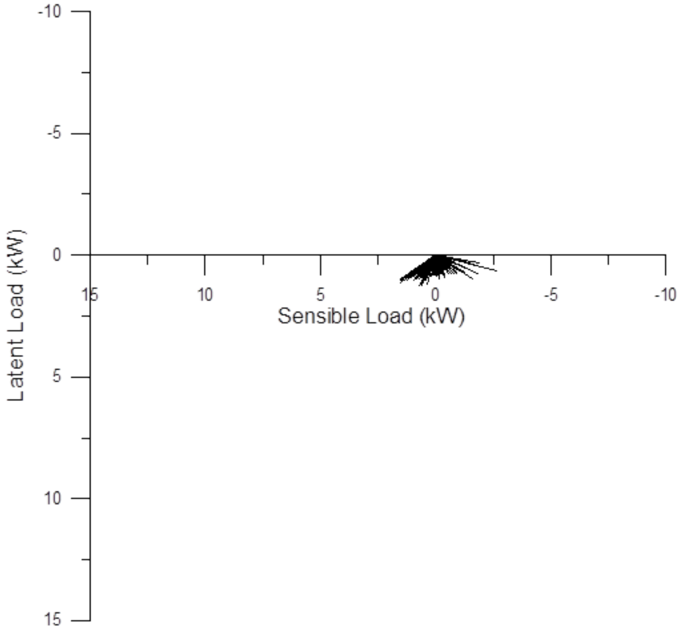


(f) Winter 2

Results from simulation of Super House D

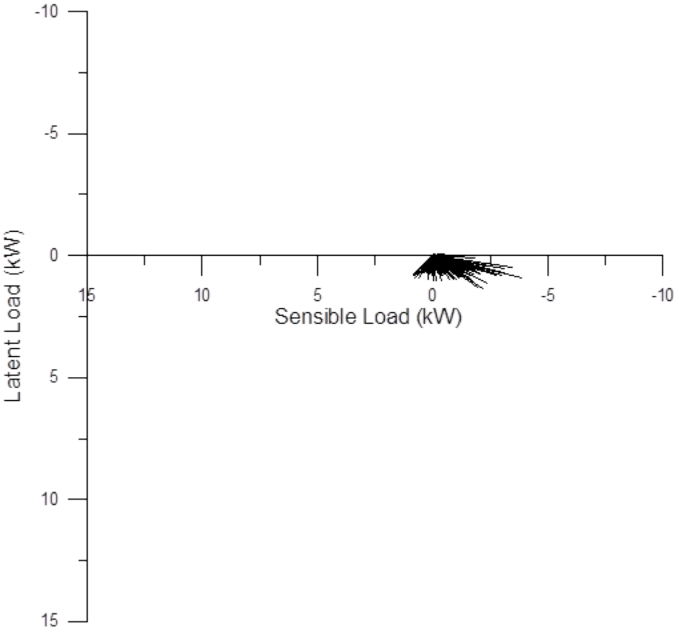


(a) Annual results

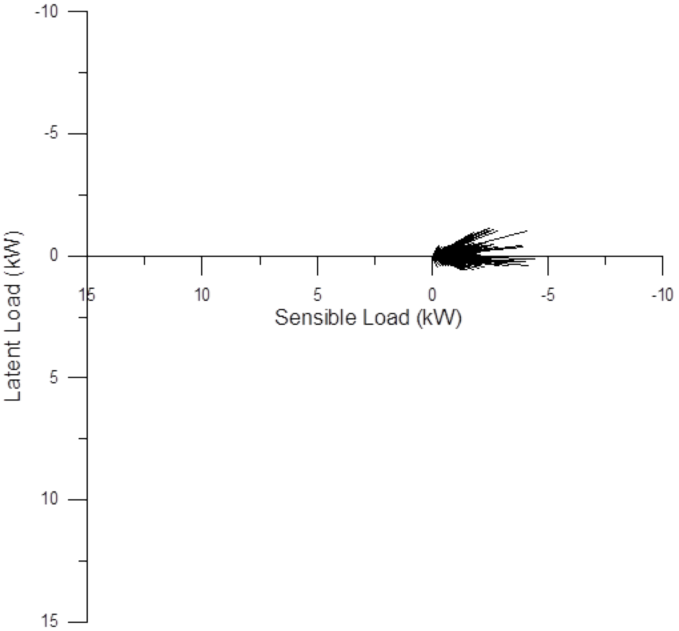


(b) Winter 1

Figure 4.18: Results from simulation of Super House D, single point plots

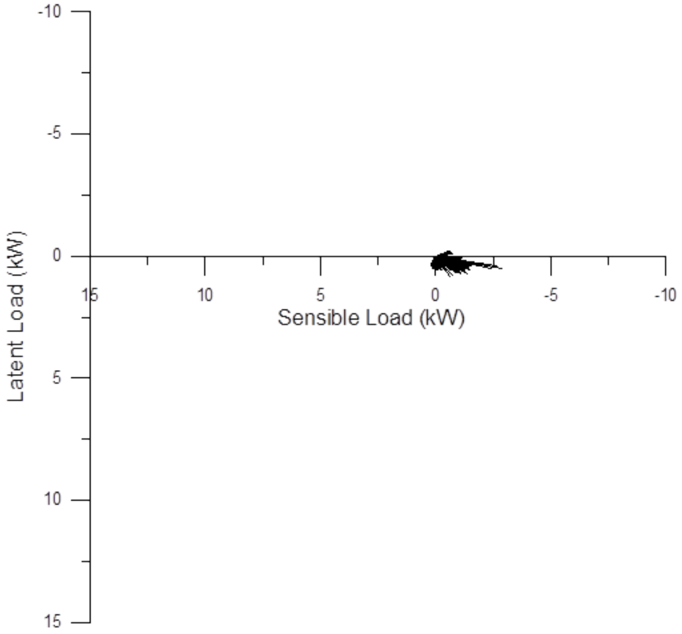


(c) Spring

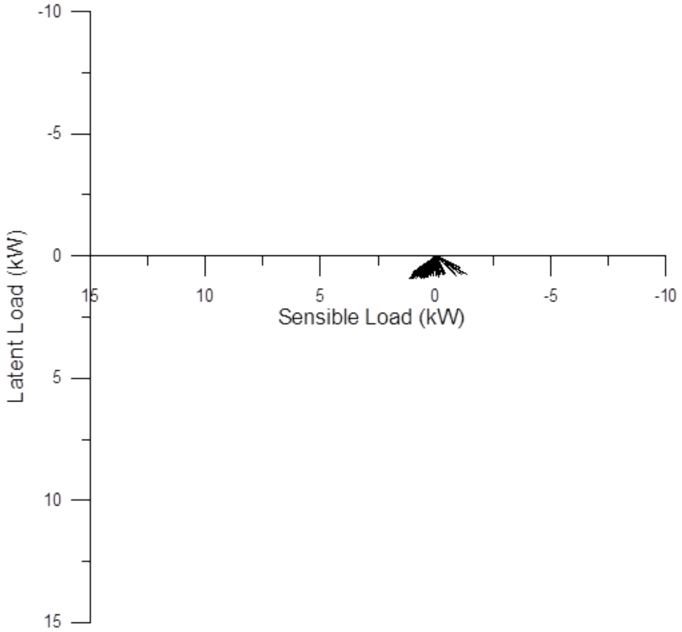


(d) Summer

Results from simulation of Super House D, single point plots



(e) Fall



(f) Winter 2

Results from simulation of Super House D, single point plots

Because there is a single condition point for the entire year, the rosettes for this house are more difficult to read. The loads shown in Figure 4.16 show that the loads are constantly changing to account for the lack of flexibility in this control scheme. The sensible cooling loads for this simulation are much larger than the sensible heating loads, and while humidification is much more common than dehumidification for this house, the relative magnitudes of each are about the same.

4.2 Superimposed Results

In this section, the different homes modelled are compared. The comparison is done in two sets. The first set will consist of the 1970's house, the 2006 Building Code house, and Super House A. The second set will consist of the the four variations of the Super House energy efficient envelope constructions. This was done to compare the relative impact of different energy saving designs. Similarly, the single point plots can also be split up for examination.

4.2.1 Comparison of Results - Set 1

This set of results includes the 1970's House, the 2006 House, and Super House A. Figure 4.19 shows the rosettes for these three houses on a single psychrometric chart.

As the houses become more airtight and well-insulated, the peak sensible heating loads (Figure 4.20) become much smaller ($14.1kW$ for the 1970 house compared to $1.6kW$ for the Super House A), while the sensible cooling loads show only a small decrease in the peak load ($6.78kW$ for the 1970 house compared to $4.73kW$ for the Super House A). The sensible cooling loads also become more frequent as the construction becomes more energy efficient. For Super House A (Figure 4.20), sensible cooling occurs about equally with humidification and with dehumidification.

Table 4.20: Peak loads for 1970 house, 2006 house, and Super House A

Load Condition	**1970 House** (kW)	**2006 House** (kW)	**Super House A** (kW)
Sensible Heating	14.1	6.85	1.6
Sensible Cooling	6.78	5.86	4.73
Dehumidification	1.05	1.09	0.81
Humidification	8.12	4.22	1.74

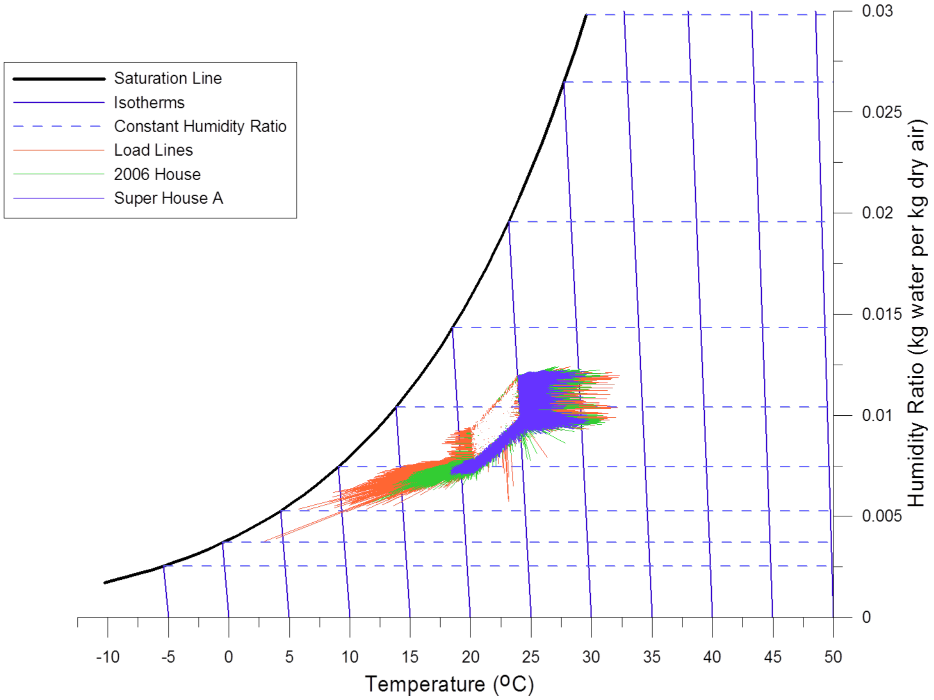


Figure 4.19: Superimposed rosettes for 1970's house, 2006 house, and Super House A

Superimposing the single point plots for these three houses results in Figure 4.20. This figure shows the reduction in the loads as the house becomes better insulated and more air-tight. The greatest change is the reduction of the sensible heating loads. Humidification loads are also reduced. Dehumidification and sensible cooling loads remain very similar for all three of the houses here, although the peak sensible cooling loads are lowered slightly as insulation is added.

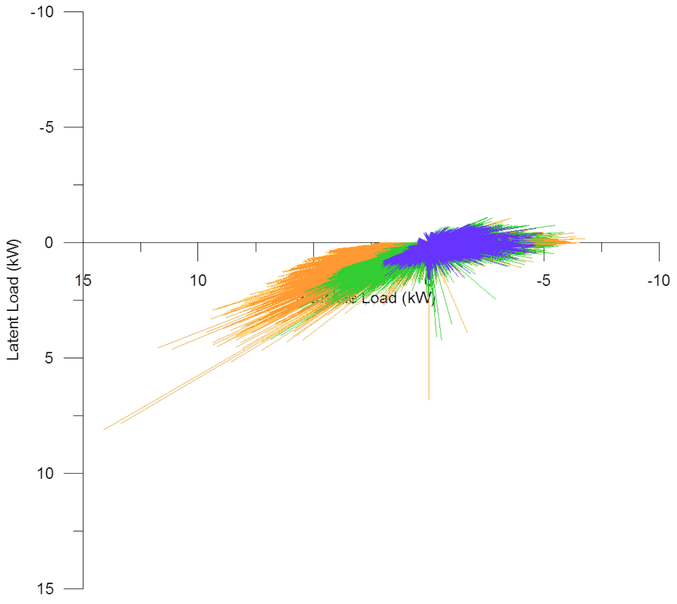


Figure 4.20: Superimposed single point plots for 1970's house, 2006 house, and Super House A

Frequency Analysis

The frequency of each load condition was discussed for each house in the appropriate section, but the results for the first set of results is compiled in Table 4.21, and then plotted in Figure 4.21 for comparison.

Table 4.21: Frequency of possible load conditions for 1970 house, 2006 house, and Super House A

Load Condition	**Hours, 1970 House**	**Hours, 2006 House**	**Hours, Super House A**
Sensible Heating Only	534	24	0.0
Sensible Heating and Humidification	3814	3862	1826
Sensible Heating and Dehumidification	43	0.0	0.0
Sensible Cooling Only	1165	709	842
Sensible Cooling and Humidification	819	1915	3129
Sensible Cooling and Dehumidification	1022	770	785
Humidification Only	522	1282	2163
Dehumidification Only	218	23	0.0
All Sensible Heating	4391	3886	1826
All Sensible Cooling	3006	3394	4756
All Humidification	5155	7059	7118
All Dehumidification	1283	793	785

The values plotted in Figure 4.21 show the total number of times each load condition occurs, regardless of any other load conditions with which it occurs in combination. Additional plots, showing load conditions in different combinations, are included in Appendix C. From the 1970 house to Super House A, the total number of occurrences of sensible heating decreases by 58%, and dehumidification decreases by 39%. The total occurrences of sensible cooling and humidification both increased, sensible cooling by 59% and dehumidification by 38%.

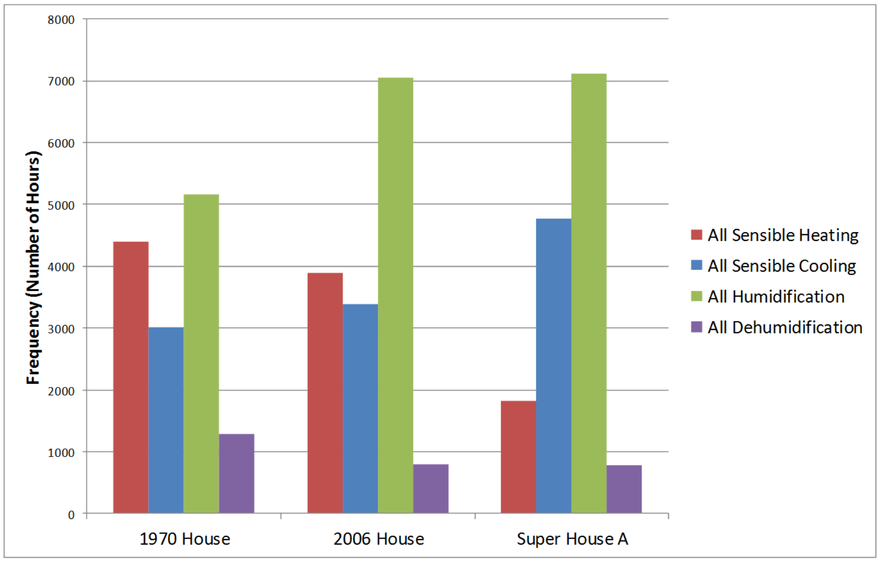


Figure 4.21: Plot of load condition frequency for 1970's house, 2006 house, and Super House A

SHR Analysis

Since the SHR is the current standard for examining the sensible-latent split for equipment loads, the SHR was calculated for each timestep for all the simulations of the Toronto houses using Equation 3.13.

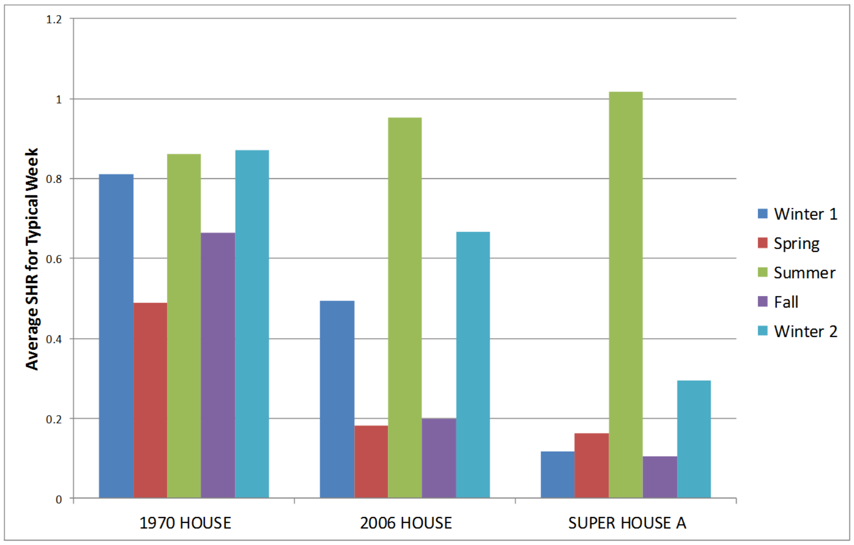
Under certain conditions the SHR will go to infinity, so all data points greater than 5 or less than -5 were discarded. The first criteria that was looked at was the maximum SHR and the minimum SHR for the entire year for the first set of results (Table 4.22). Table 4.22 also shows the average positive and negative SHR for each house. All values in Table 4.22 are for the entire season, not just the typical week examined. For the 1970 house, 15 values were discarded, for the 2006 house 318 or 3.6% of the values were discarded, and for Super House A, 294 or 3.4% of the values were discarded.

Table 4.22: Annual maximum and minimum sensible heat ratios for each house

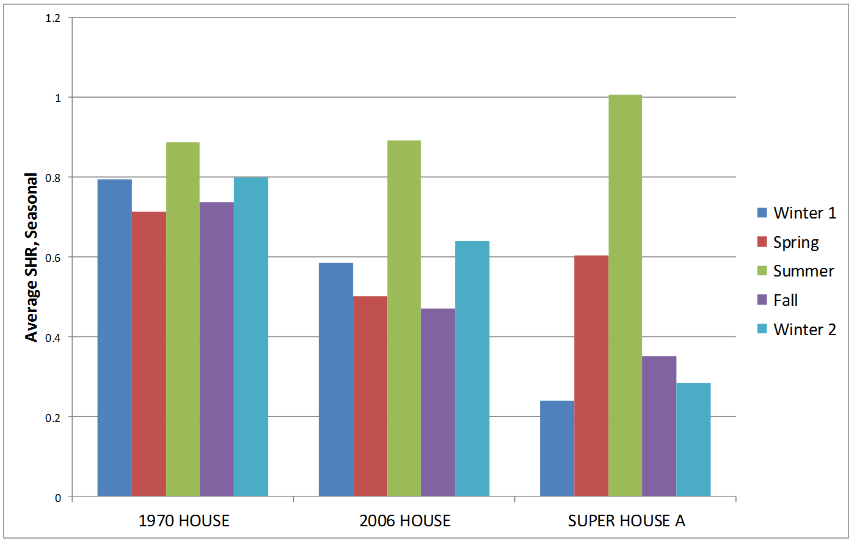
	1970's House	**2006 House**	**Super House A**
Maximum SHR	4.8	4.94	4.95
Minimum SHR	-4.75	-4.5	-4.86
Average SHR, positive	0.897	0.843	0.997
Average SHR, negative	-0.859	-0.851	-0.839
Average SHR, Winter 1	0.795	0.586	0.240
Average SHR, Spring	0.713	0.502	0.604
Average SHR, Summer	0.888	0.893	1.006
Average SHR, Fall	0.737	0.471	0.351
Average SHR, Winter 2	0.800	0.639	0.285

The average SHR for the typical week for each season, and for the entire season are plotted in Figure 4.22. As expected, Figures 4.22a and 4.22b are similar to each other, but there are differences due to the increased number of data points when the entire season is considered. The most notable differences are seen with the SHR for the shoulder seasons. If only the typical week is considered, the values for the SHR tend to be fairly low. Once the entire season is considered, the SHR for the spring and fall are increased.

Plotting the average SHR values (Figure 4.22) shows that the absolute value of the SHR is reduced as the standard of construction is improved from the 1970 house to Super House A, except for the summer, which increases. The plot also shows that the average SHR is significantly reduced for the winter as insulation is added and infiltration is reduced. Shoulder seasons require a more in-depth examination, which will be discussed later in this section.



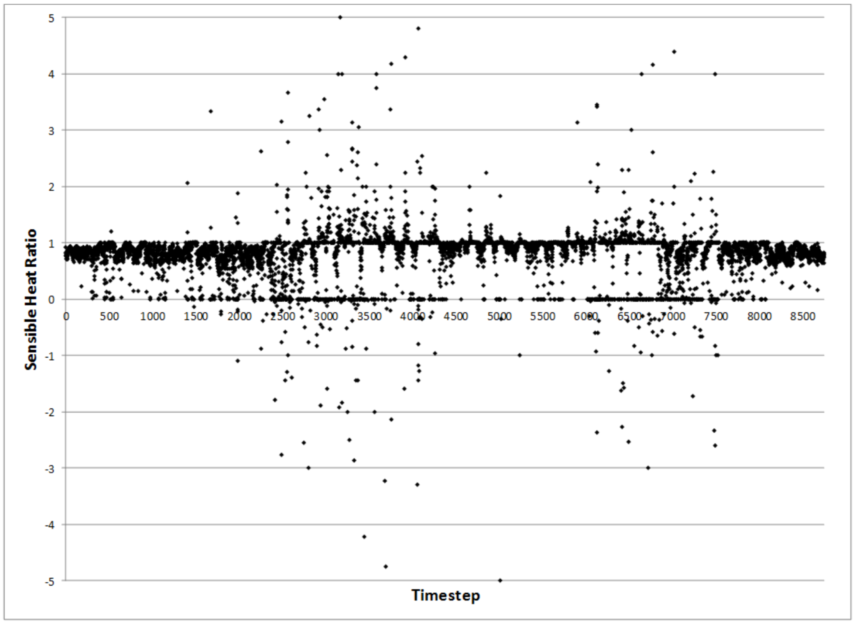
(a) Average SHR values for a typical week in each season



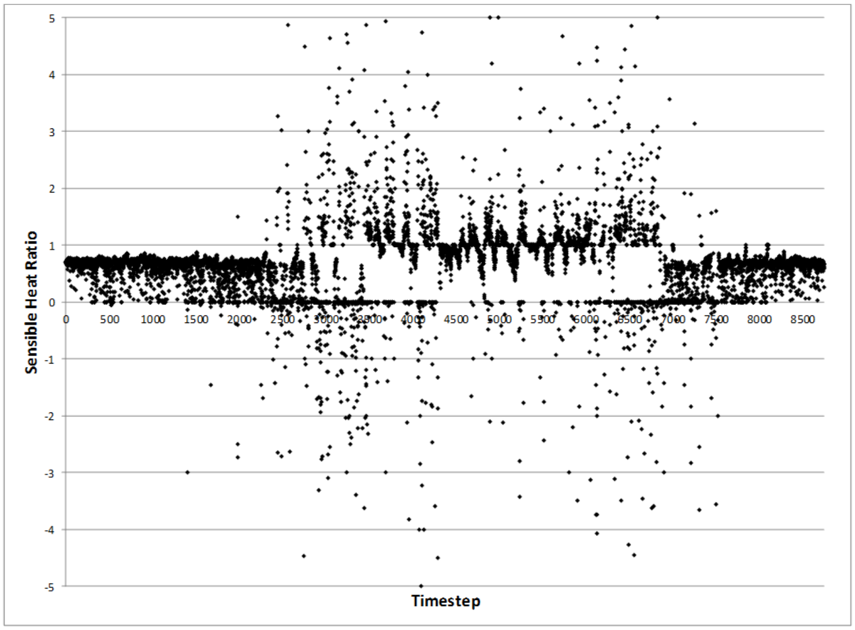
(b) Average SHR values for each season

Figure 4.22: Average sensible heat ratios for each house

Plotting the SHR for each timestep in a simulation shows the distribution of the SHR throughout the year, where the loads switch over from heating to cooling, and potentially where any changes in whether humidification or dehumidification is dominant will occur.



(a) 1970 House



(b) 2006 House

Figure 4.23: SHR for each timestep in the year

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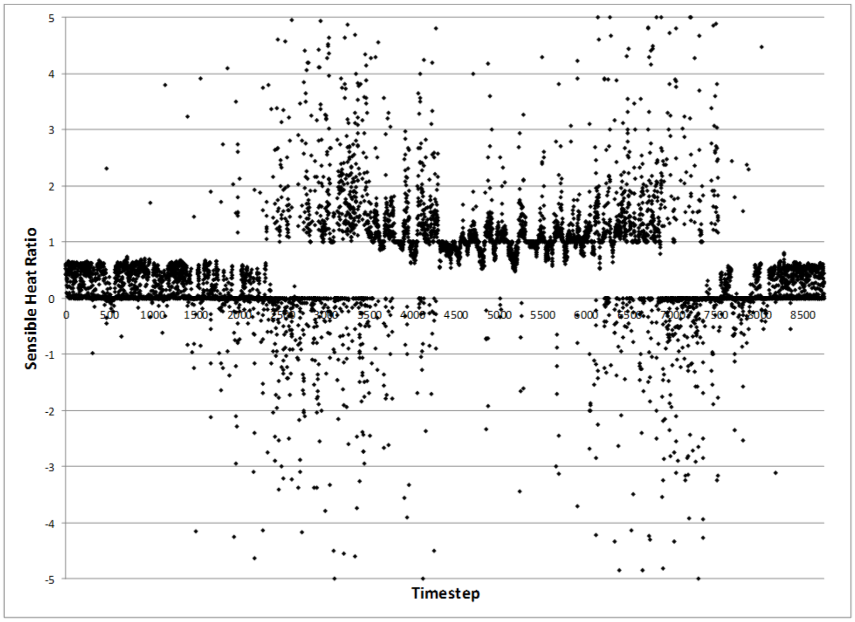


(c) Super House A

SHR for each timestep in the year

The plots in Figure 4.23 show that as the standard of construction is improved, the heating loads shift from being almost completely sensible heating dominated with SHR values between 0 and 1, to a case where the SHR shows more sensible cooling, and the SHR when sensible heating is present is much lower. Super House A also shows much more variation in the SHR during the shoulder seasons than the 1970 house.

4.2.2 Comparison of Results - Set 2

This set of results consists of Super House A, Super House B, Super House C, and Super House D. In Figure 4.24, the results for Super House C are shown in black, but are very hard to see due to the similarity to the results from Super House A (shown in blue). Super House D, with the alternate control scheme, is very different from the other three houses when plotted on the psychrometric chart. Peak loads are compared in Table 4.23.

Table 4.23: Peak loads for Super Houses A, B, C, and D

Load Condition	**Super House A** (kW)	**Super House B** (kW)	**Super House C** (kW)	**Super House D** (kW)
Sensible Heating	1.6	0.15	1.61	2
Sensible Cooling	4.73	6.3	4.49	4.96
Dehumidification	0.81	0.92	0.81	1.13
Humidification	1.74	1.71	1.81	1.92

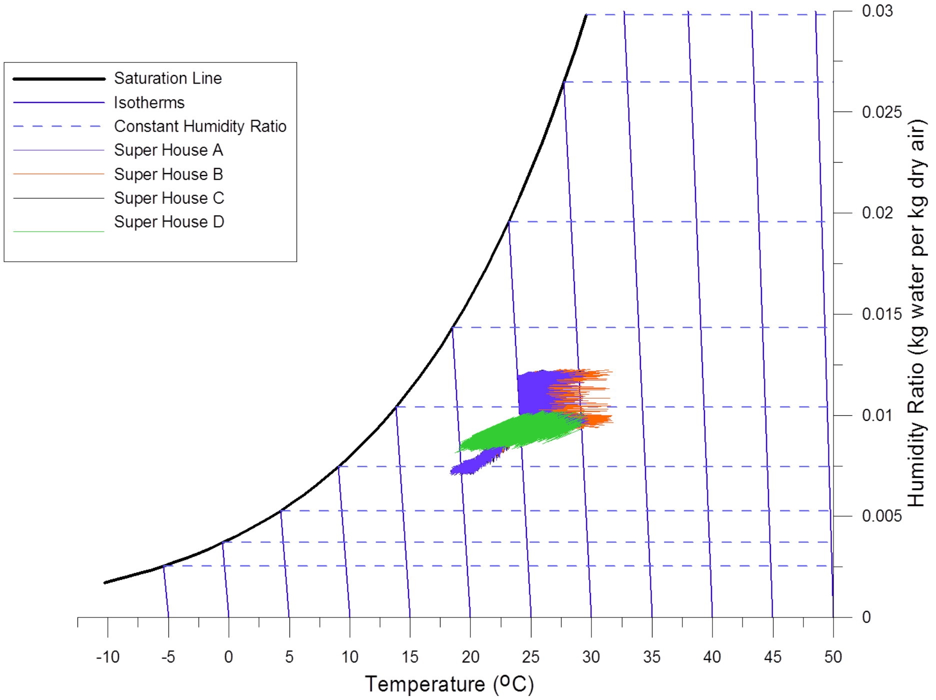


Figure 4.24: Superimposed rosettes for Super Houses A, B, C, and D

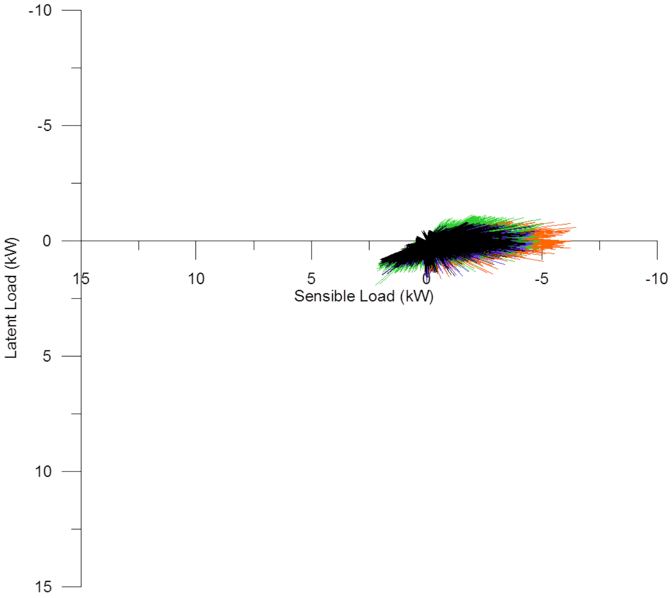


Figure 4.25: Superimposed single point plots for Super Houses A, B, C, and D

On the single point plot (Figure 4.25), the similarity between the equipment loads for these houses is very clear. Although there are variations in the loads, these variations are small, and the general shape of the single point plots is the same for all four houses. When comparing Super House D with Super House A and C, which have the same construction and occupancy, small changes in the equipment loads are shown but overall the loads for these three houses are very similar despite the changes to the setpoints.

Figure 4.25 shows that increasing the occupancy (Super House B) has eliminated most of the sensible heating loads, and increased the frequency and magnitude of the sensible cooling loads. The sensible heating loads for this house are much smaller than the sensible heating loads for the houses with only two occupants. Sensible cooling loads for Super House B are greater and more frequent than the houses with only two occupants.

Super House C, with dynamic shading, has very similar loads to Super House A. Overall, there is some reduction in the cooling load for Super House C, but for some timesteps the cooling load is actually increased. External shading may be more effective at reducing or shifting space conditioning loads for this house.

Frequency Analysis

As with the first group, the frequency at which each load condition or combination of load conditions occurs can be compared.

Table 4.24: Frequency of possible load conditions for Super Houses A, B, C, and D

Load Condition	**Hours, Super House A**	**Hours, Super House B**	**Hours, Super House C**	**Hours, Super House D**
Sensible Heating Only	0.0	0.0	0.0	0.0
Sensible Heating and Humidification	1826	15	1911	2720
Sensible Heating and Dehumidification	0.0	0.0	0.0	0.0
Sensible Cooling Only	842	1058	842	47
Sensible Cooling and Humidification	3129	5661	3032	4085
Sensible Cooling and Dehumidification	785	1024	785	1880
Humidification Only	2163	1002	2176	28
Dehumidification Only	0.0	0.0	0.0	0.0
All Sensible Heating	1826	15	1911	2770
All Sensible Cooling	4756	7743	4659	6012
All Humidification	7118	6678	7119	6833
All Dehumidification	785	1024	785	1880

Unlike the first set of results, there are no immediate trends to be seen. The results for Super House A and Super House C are very similar, since the only difference is the addition of dynamic shading control to Super House C. Super House B with double the occupancy is very different from any of the other houses simulated because of the increased sensible and latent internal gains.

Figure 4.26 shows the frequency of each load condition for the highly insulated houses. This plot shows that Super House B requires significantly more sensible cooling than Super

House A (a 62% increase), and Super House D requires both more sensible cooling and more dehumidification than Super House A (increases of 26% and 139% respectively).

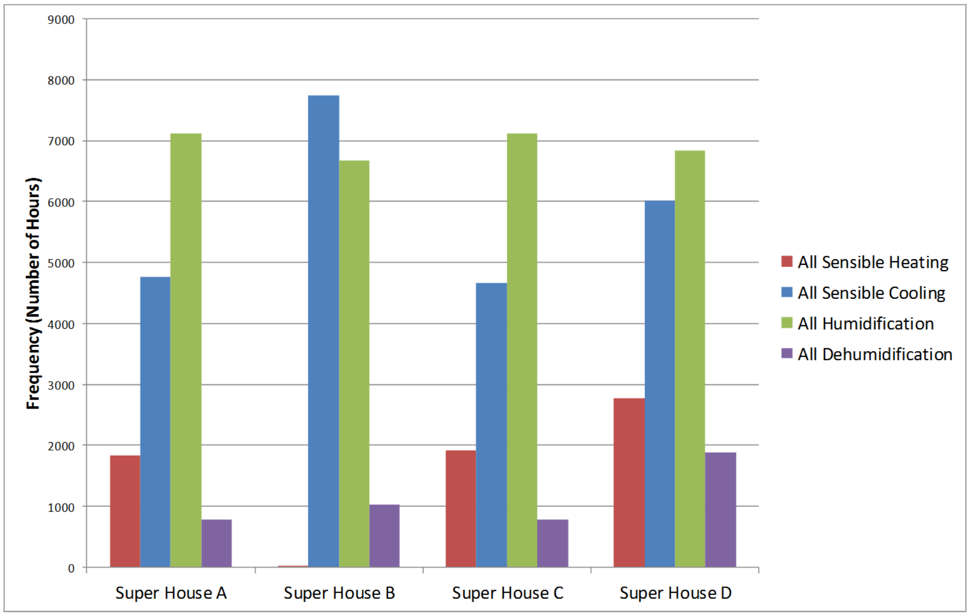


Figure 4.26: Plot of load condition frequency for Super House A, B, C, and D

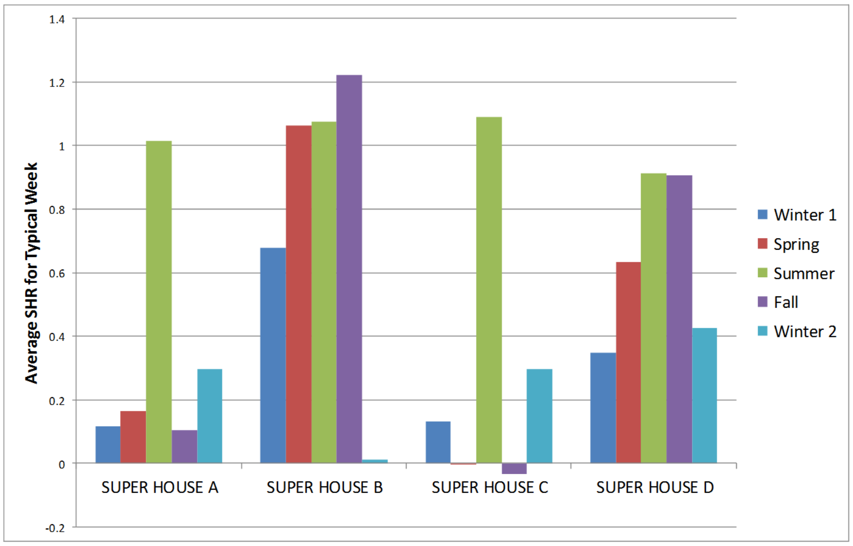
SHR Analysis

After examining the frequency of each load condition, the SHR was compared for the four houses in this group of results. Once again, the average values shown in Figure 4.25 are for the entire season, not just the typical week. Once again, values that were too high or two low were discarded. For Super House A, 294 (3.4%) of the SHR values were discarded, for Super House B 520 values (5.9%) were discarded, for Super House C 303 values (3.5%) were discarded, and for Super House D 401 values (4.6%) were discarded.

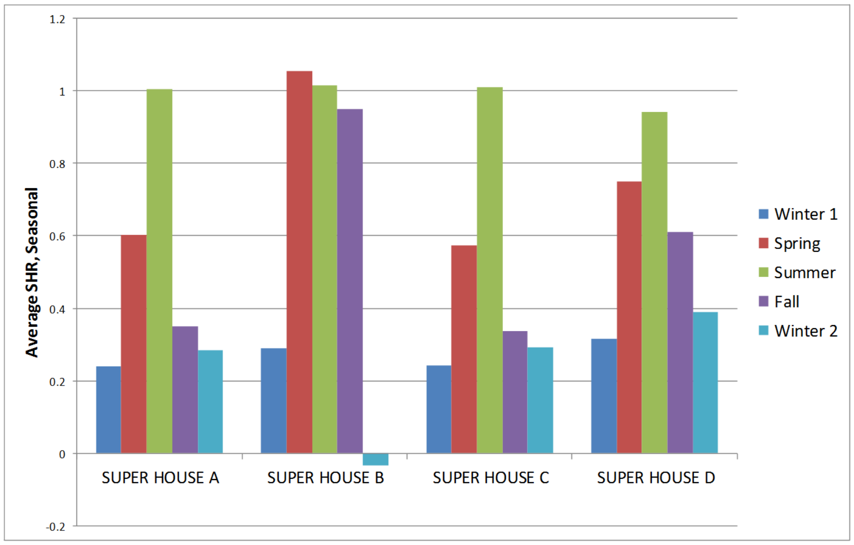
Table 4.25: Annual maximum and minimum sensible heat ratios for each house

	Super House A	**Super House B**	**Super House C**	**Super House D**
Maximum SHR	4.95	4.95	4.93	4.93
Minimum SHR	-4.86	-4.94	-4.87	-4.92
Average SHR, positive	0.997	1.389	0.979	0.937
Average SHR, negative	-0.839	-1.068	-0.869	-0.993
Average SHR, Winter 1	0.240	0.291	0.243	0.316
Average SHR, Spring	0.604	1.054	0.573	0.750
Average SHR, Summer	1.006	1.015	1.009	0.942
Average SHR, Fall	0.351	0.950	0.337	0.611
Average SHR, Winter 2	0.285	-0.033	0.293	0.388

Plotting the average SHR for the typical weeks and the entire season and comparing these values from house to house does not show the dramatic differences that the first group of houses showed (Figure 4.22).



(a) Average SHR values for a typical week in each season

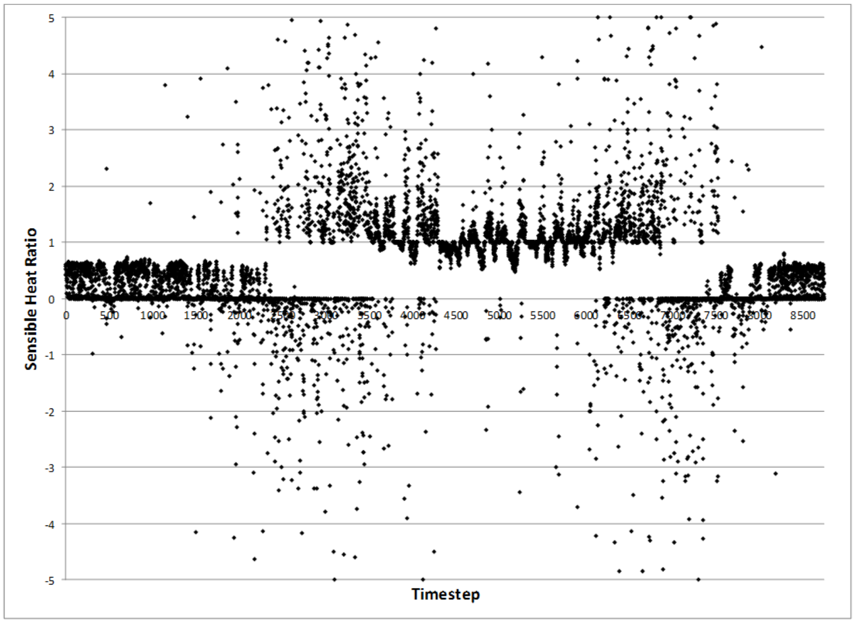


(b) Average SHR values for each season

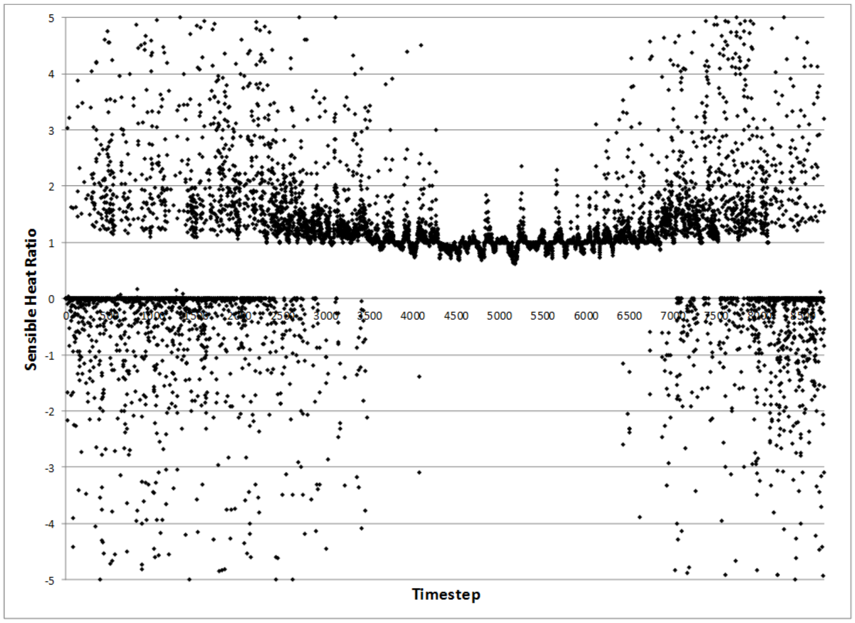
Figure 4.27: Average sensible heat ratios for each house

Figure 4.27 shows that for the highly insulated houses, the occupancy makes the greatest difference in the equipment loads. The house with four adults requires much less sensible heating than the other houses, and the average SHR is negative for the second winter for this house. The other significant difference between houses in Figure 4.27 is the increase in the average fall SHR for Super House D, which is about twice that of the average fall SHR of Super House A.

The sensible heat ratios for each timestep for the highly insulated houses are plotted in Figure 4.28.

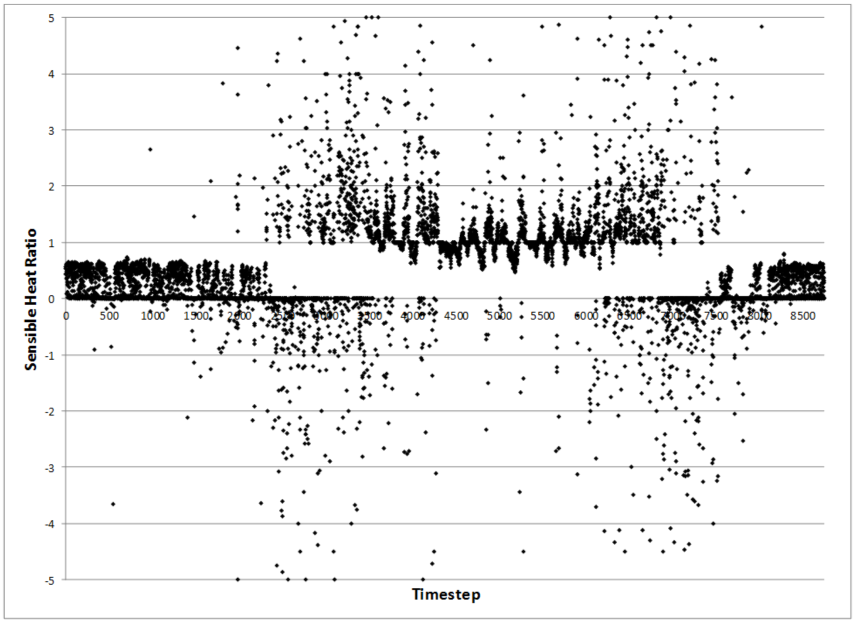


(a) Super House A

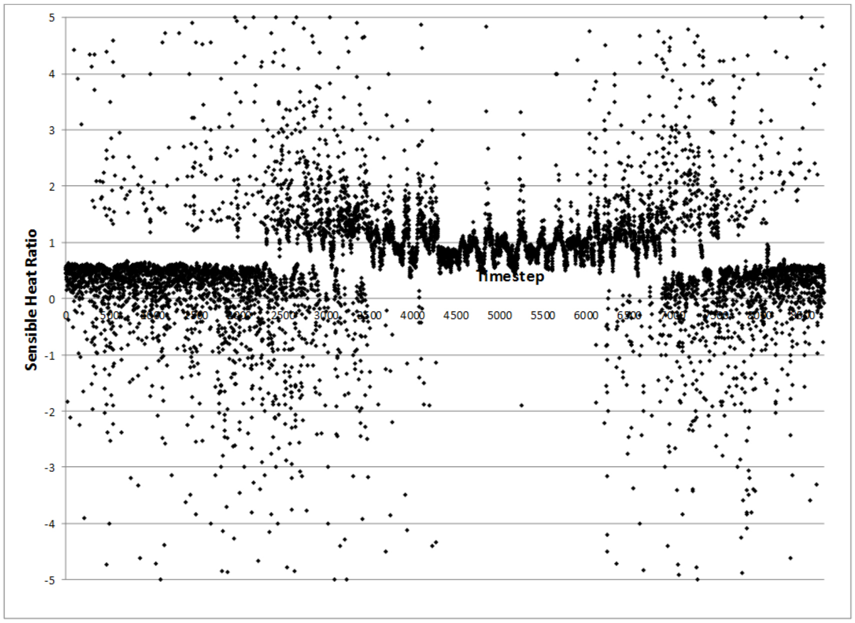


(b) Super House B

Figure 4.28: SHR for each timestep in the year



(c) Super House C



(d) Super House D

SHR for each timestep in the year

The SHR plots for Super House A and Super House C are almost identical. Super House B, with the increased occupancy, shows that the loads during all seasons other than the summer are much more variable than the other houses, and sensible cooling is very common with this house.

4.3 Other Locations

To investigate the effect of climate on the equipment loads within a highly insulated house, four different locations across Canada were selected and simulated. The locations chosen were Winnipeg, Vancouver, Whitehorse, and Shearwater. Super House A was used for these simulations. No changes to the model were made other than the climate files and locations.

Barometric pressure is required to plot the rosettes, and can be taken from records from local weather stations. Pressure data from 2010 was used for Whitehorse, and from 2001 for Shearwater. The simulation year for Shearwater in ESP-r was 1973 but climate data from that year was unavailable.

Table 4.26: Peak loads in kW for the entire year for Super House A in different climates

Load Condition	**Sensible Heating**	**Sensible Cooling**	**Dehumidification**	**Humidification**
Toronto	1.6	4.73	0.81	1.74
Winnipeg	2.88	4.92	0.96	2.02
Vancouver	0.84	4.57	0.05	1.71
Whitehorse	3.38	4.51	0.0	1.61
Shearwater	1.6	4.77	0.5	1.83

Table 4.27: Total kWhr delivered to Super House A in different climates

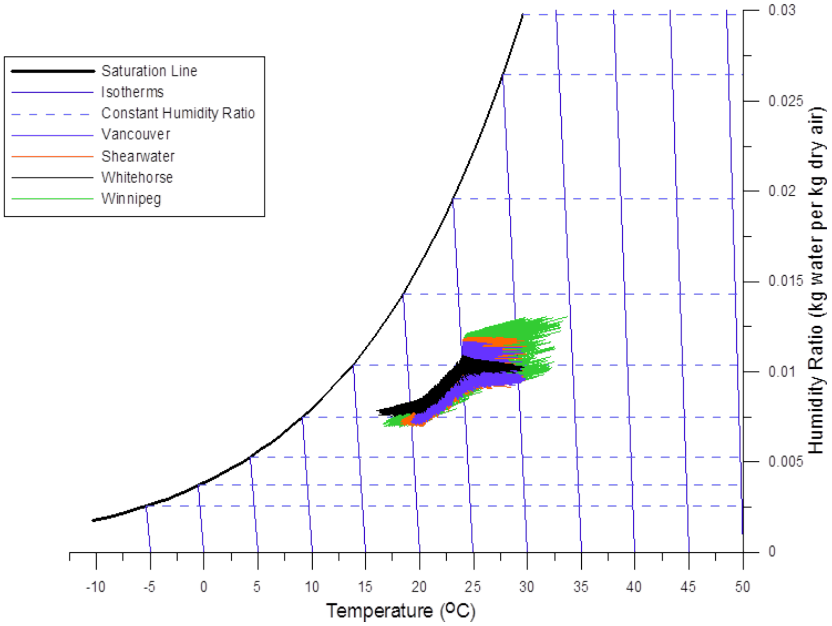
Load Condition	**Sensible Heating**	**Sensible Cooling**	**Dehumidification**	**Humidification**
Toronto	913	5296	183	1.74
Winnipeg	2243	5306	86	4817
Vancouver	171	5483	0.10	2774
Whitehorse	2981	3611	0.0	5804
Shearwater	590	4661	64	3558

The frequency of each load condition is in Table 4.28.

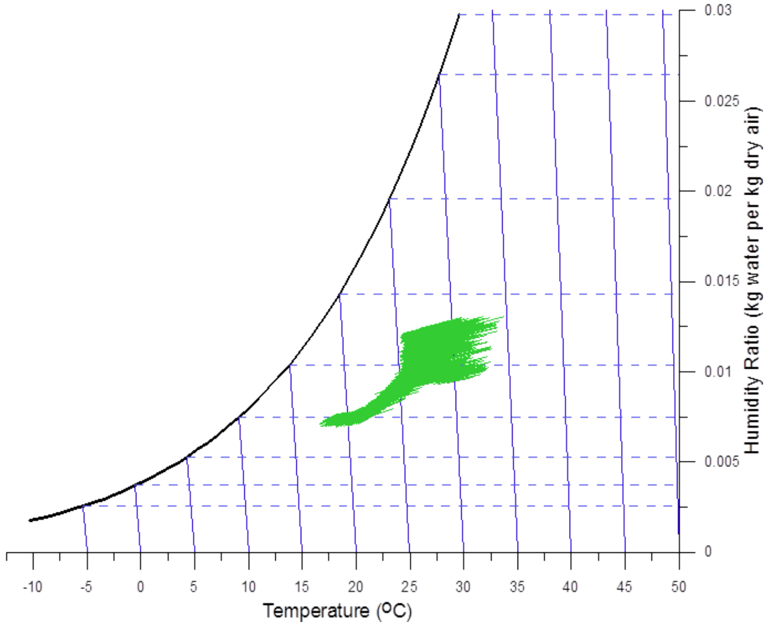
Table 4.28: Frequency of possible load conditions for different locations in Canada

Load Condition	**Hours, Toronto**	**Hours, Winnipeg**	**Hours, Vancouver**	**Hours, Whitehorse**	**Hours, Shearwater**
Sensible Heating Only	0.0	0.0	0.0	0.0	0.0
Sensible Heating and Humidification	1826	2581	683	3154	1359
Sensible Heating and Dehumidification	0.0	0.0	0.0	0.0	0.0
Sensible Cooling Only	842	701	1060	4	1163
Sensible Cooling and Humidification	3129	3350	4291	3628	3114
Sensible Cooling and Dehumidification	785	441	4	0.0	450
Humidification Only	2163	1682	2721	1974	2637
Dehumidification Only	0.0	0.0	0.0	0.0	0.0
All Sensible Heating	1826	2581	683	3154	1359
All Sensible Cooling	4756	4492	5355	3623	4727
All Humidification	7118	7613	7695	8756	7110
All Dehumidification	785	441	4	0.0	450

The rosettes for each location (not including the Toronto house, which has already been presented in Figure 4.8) are below in Figure 4.29, and the single point plots are in Figure 4.30. Typical weeks for each location are included in Appendix B.

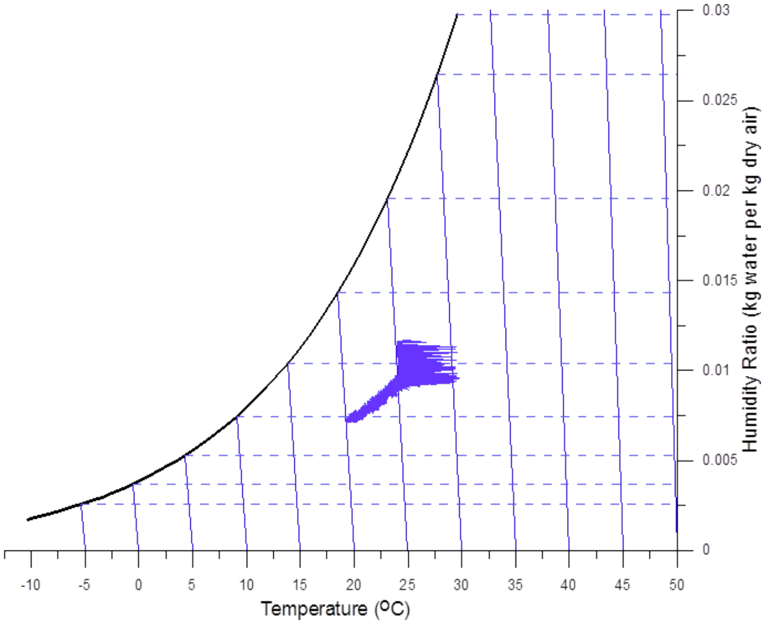


(a) All locations

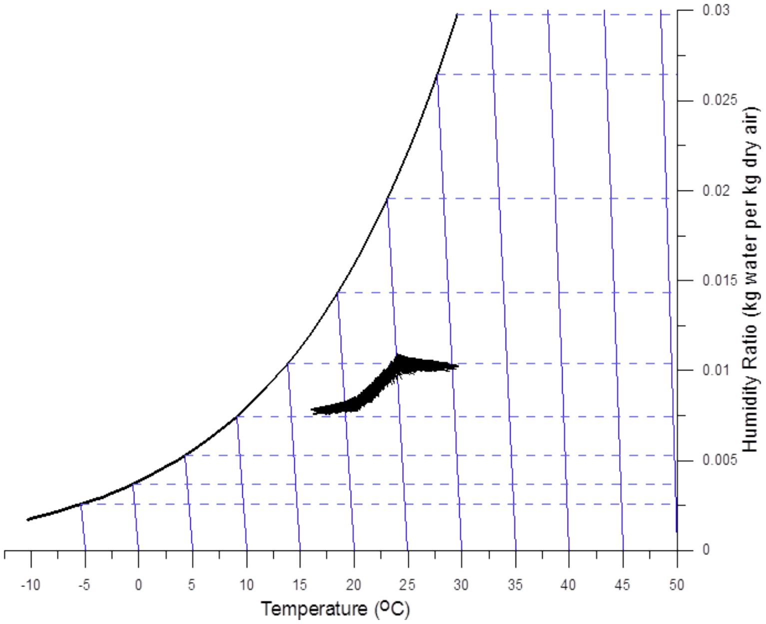


(b) Winnipeg, Manitoba

Figure 4.29: Rosettes for different locations across Canada

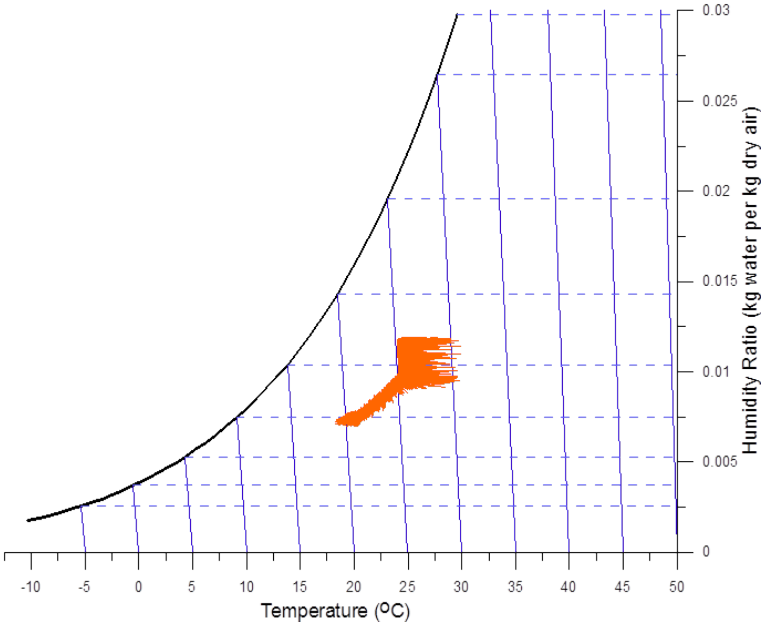


(c) Vancouver, British Columbia



(d) Whitehorse, Yukon Territory

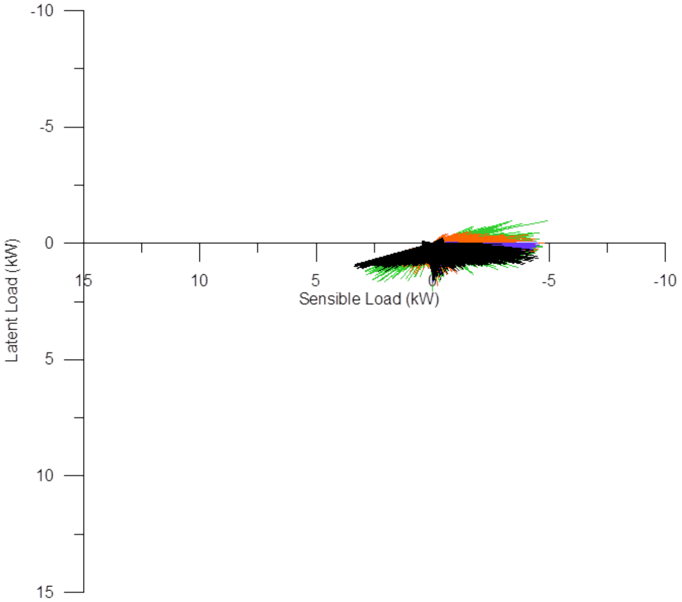
Rosettes for different locations across Canada



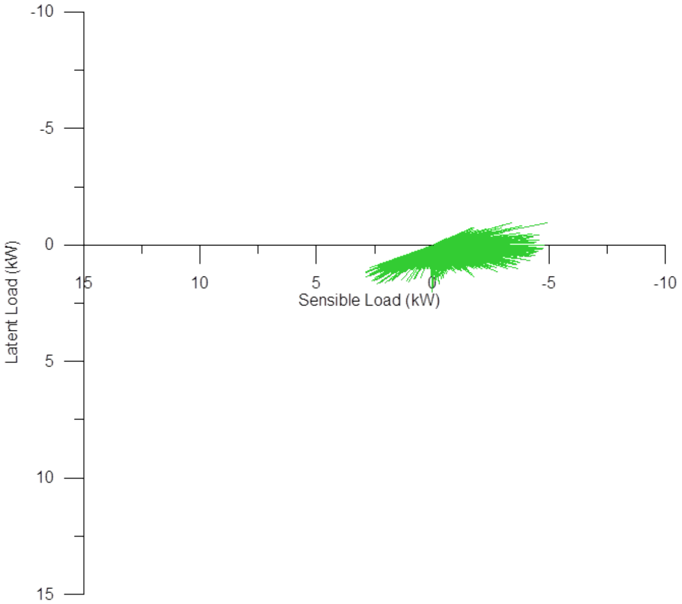
(e) Shearwater, Nova Scotia

Rosettes for different locations across Canada

The rosettes show that the location plays a key role in the distribution of the load lines around the rosette. However, when the equipment loads are plotted directly on to the single point plots, the plots become very similar as seen in Figure 4.30a.

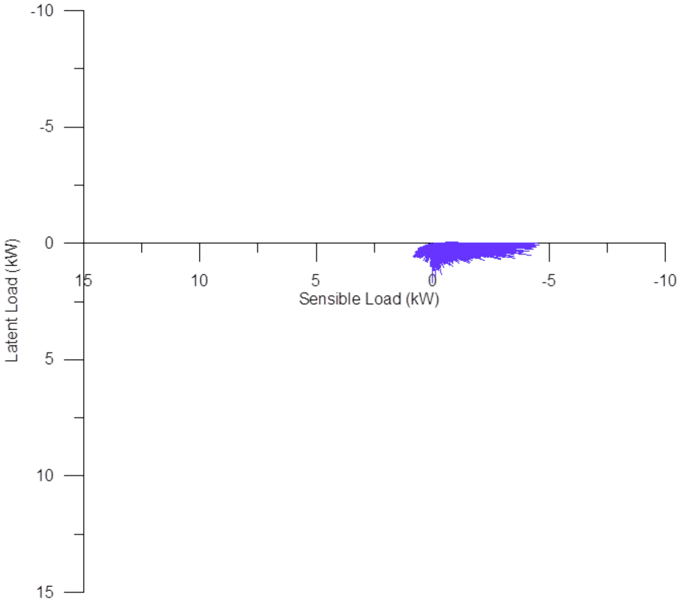


(a) All locations

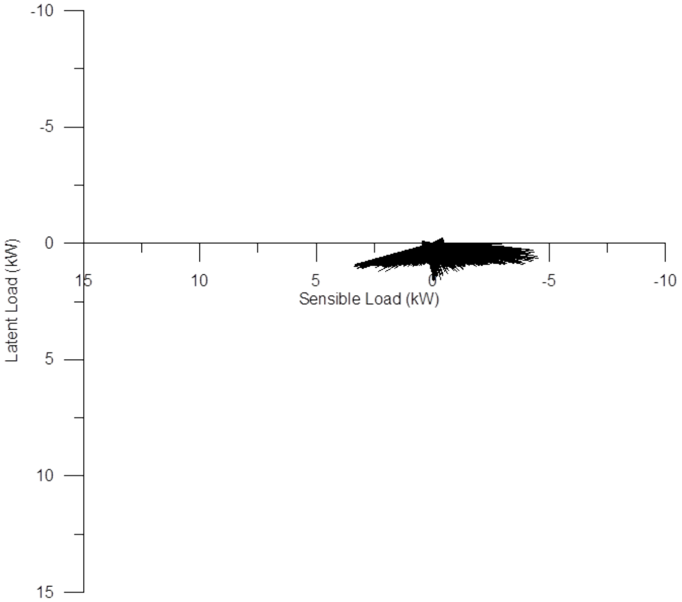


(b) Winnipeg, Manitoba

Figure 4.30: Single point plots for different locations across Canada

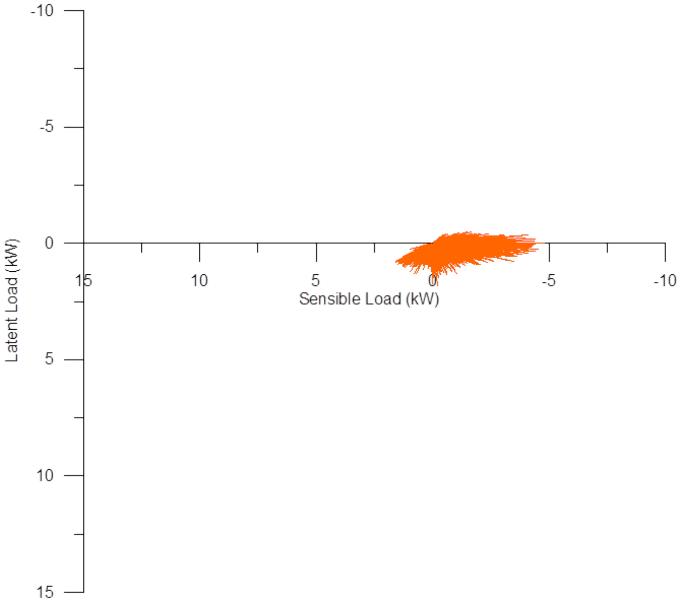


(c) Vancouver, British Columbia



(d) Whitehorse, Yukon Territory

Single point plots for different locations across Canada



(e) Shearwater, Nova Scotia

Single point plots for different locations across Canada

Comparing the single point plots, the magnitude of the loads is not significantly affected by the location. However the rosettes show the distribution of the loads changes for each location. This suggests that the actual capacity of the equipment installed might not be as important as the controls and setpoints for the equipment.

The SHR for each location was calculated. Maximum and minimum SHRs and the average SHR for each season are included in Table 4.29. SHR plots will be included in Appendix B with the typical weeks.

Table 4.29: Annual maximum and minimum sensible heat ratios for each house

	Toronto	**Winnipeg**	**Vancouver**	**Whitehorse**	**Shearwater**
Maximum SHR	4.95	4.947	4.938	4.933	4.909
Minimum SHR	-4.86	-4.917	-4.933	-4.929	-4.909
Average SHR, positive	0.997	0.987	1.264	1.006	1.054
Average SHR, negative	-0.839	-0.940	-0.927	-0.971	-0.890
Average SHR, Winter 1	0.240	0.356	0.088	0.412	0.169
Average SHR, Spring	0.604	0.563	0.753	0.360	0.408
Average SHR, Summer	1.006	0.999	1.102	0.868	1.004
Average SHR, Fall	0.351	0.312	0.330	0.228	0.349
Average SHR, Winter 2	0.285	0.363	0.033	0.573	0.173

From the rosettes, the single point plots, and an examination of the SHRs for the houses across Canada, the location of a house does play an important role in the sensible-latent split of the equipment loads.

Chapter 5

Conclusions

5.1 Conclusions from Work Presented

The magnitude of the loads change from house to house, but as the standard of construction changes the frequency of each load condition also changes. Each load condition and combination of load combinations changes differently, depending on whether an improvement in construction or a change will primarily affect the sensible loads or the latent loads. For the first set of results compared, increasing the thermal insulation and decreasing the amount of infiltration through the envelope significantly reduces sensible heating loads, while sensible cooling loads remain close in magnitude. These houses also experienced a shift in the latent loads as the standard of construction increases. For the second set of results examined, increasing the occupancy results in the greatest change in the loads, and shift in the distribution of the loads around the rosettes.

5.1.1 Were the Project Objectives Met?

The first objective was to develop a graphical method for examining the equipment loads for a space, taking into account both sensible and latent loads. A graphical method to create the rosettes was created, and it has been shown to be useful when comparing the loads of different houses. This objective was met.

The second objective was to determine if latent equipment loads are dominant in high efficiency houses in Canada. While the latent equipment loads are different for high efficiency homes than for homes built using standard construction materials and methods, the latent equipment loads were not as dominant as expected for the houses in this study. There was a significant increase in the frequency of sensible cooling. This objective was also met, even though the simulation results were not what was expected.

The final objective was to use the graphical method to show the differences in equipment loads for different climate zones within Canada. This objective was met, with the rosettes and single point plots shown in Figures 4.29 and 4.30. These simulations show that even though the loads for the different locations will be similar, the rosettes may appear very different. This objective was also met.

This thesis project has laid the framework for a graphical method of analysis of equipment loads and behaviour for housing in Canada. Used in conjunction with current methods and guidelines, the methods developed here can provide important background information on the magnitude and distribution of the sensible and latent loads present.

5.1.2 Conclusions: Group 1

This section consists of conclusions from a comparison of the 1970 house, the 2006 house, and Super House A, all located in Toronto, Ontario.

Increasing thermal insulation and reducing air infiltration through the building envelope has a significant impact on the equipment loads. The peak sensible heating load is reduced from $14.1kW$ to $1.6kW$, and the frequency of sensible cooling increases from 3006 hours to 4756 hours when the 1970 house is compared to Super House A.

Neither the 1970 house nor the 2006 house were dominated by dehumidification, nor is Super House A. All of these models assumed that the windows were operable but remained closed throughout the entire simulation. The rosettes for the three houses in the group showed a dramatic change as the construction was improved.

5.1.3 Conclusions: Group 2

The Super Houses all used the same levels of thermal insulation and air infiltration. In this set of results, other factors such as occupancy and alternate control schemes were studied.

Of the highly insulated houses located in Toronto, changing the occupancy had the biggest effect on the equipment loads. Sensible heating was almost completely eliminated due to larger internal gains, and the latent loads saw an increase in the dehumidification requirements and a decrease in the humidification requirements.

All other factors being equal, dynamic shading using internal Venetian blinds has very little effect on the space conditioning loads for the highly insulated construction. Dynamic shading does slightly reduce the peak loads, but there is no noticeable change in the sensible-latent split for this house. Other methods such as external shading will have a greater effect on the loads.

The distribution of the load lines on the rosettes is as useful as the length of the load lines. The relative length of the load lines is more important than the actual length of the load lines on the rosettes. On the single point plots, actual length and distribution are most important.

All of the houses simulated show some very short humidification or dehumidification lines at some time during the year. These lines can likely be eliminated by adding some flexibility to the controls.

Examining the latent loads alone, all of the super insulated houses in this study showed that humidification loads were much more frequent, and much larger than dehumidification loads. None of these houses were dominated by dehumidification loads. While reducing the infiltration through the building envelope from $6.68ach$ to $0.8ach$ shifted the sensible loads from heating dominated to cooling dominated, no such dramatic shift was seen with the latent loads. Examining the difference between Super House B and the other super insulated houses, internal sources of moisture are the most important factor in determining whether or not supplemental moisture control is needed.

It was observed that while the house with the alternate control scheme creates a rosette that looks very different then the other three houses, the single point plot for this house is not significantly different from the other houses. This suggests that small changes in the setpoints do not affect the overall distribution of loads, and do not need extensive investigation during the design phase.

The extremely well insulated house with the greatest difference from Super House A was the house with increased occupancy. By doubling the number of people in the house sensible heating loads were almost completely eliminated, and the house required sensible cooling throughout the year.

From the simulation results, it is very important to consider occupancy when designing highly insulated houses.

5.2 Potential Applications

This work has implications on the way HVAC systems in houses are designed, installed, and operated. As the standard of construction of the houses simulated goes up, the length of the cooling seasons increases, even though the magnitude of the cooling loads does not change significantly. Different cooling equipment may be necessary as equipment loads change. Since cooling equipment may be running more frequently for a very efficient house, investing in higher quality cooling equipment or investigating other methods to maintain a comfortable temperature within the house may be necessary. Meanwhile, the heating equipment used can also be examined to make sure that it is not larger than necessary to maintain thermal comfort.

These results have shown that occupancy will have a significant effect on the loads within high efficiency houses. It would be beneficial to develop a protocol for running multiple simulations showing different occupancy scenarios to be used in future work or by industry. These scenarios could be used to investigate how equipment loads will change if the occupancy changes, to see if the equipment chosen for a particular house will need to be changed to handle different loads, especially if the sensible-latent split changes.

Mould problems caused by excess moisture in housing on reserves and in the high Arctic have been known to be a problem for some time, as discussed in [Baril et al., 2013]. The methods of analysis developed here could be used to look for areas of improvement. The research here could be used to characterize loads within specific houses and potentially determine the best possible course of action in different circumstances. The method for analysing sensible and latent loads developed in this thesis could be applied to a specific house that is known to have moisture problems, and recommendations for changing the equipment to resolve the problems in that particular house could be made.

5.3 Future Work

There are many possibilities to expand on the work presented in this thesis. While a number of options will be presented in detail here, it is recommended that the focus be on developing a model of an occupied house, and then on examining the impact of different moisture generation rates within the house and on the impact of different control schemes.

5.3.1 Control Schemes

Additional simulation runs should be performed to investigate the effects of different control options. Both the control scheme for the house itself and the control scheme for the HRV could be investigated.

The control scheme used in this study was fairly rigid, and was not changed to account for different conditions. Control setback could be implemented to account for the occupants turning down the heating setpoint at night, and during periods when the house is unoccupied. This would provide a more realistic scenario. Adding some flexibility to the setpoints could also be implemented.

The HRV in this study operated constantly, throughout the entire year, but it could be controlled based on the weather, or on occupancy. This could change both the sensible and latent loads on the HVAC equipment in the house.

Different control schemes set up for summer and winter are not uncommon - an air conditioning unit disabled in October and not restarted until April or May, for example. In this case, the air conditioning unit will not be available while it is considered disconnected, so a house that requires cooling during what is traditionally considered the heating season (e.g. Super House B with four occupants) will have periods where the space overheats to some extent, unless the occupants step in to do something to make the space more comfortable. The circumstances under which this occurs, and how often it becomes a problem could affect when cooling or heating equipment is switched on or off for the season, which will in turn have implications for the cost of operating the equipment.

5.3.2 Other Possible Variations

Adding external shading will affect sensible load but not the latent load. The simulation of Super House C showed that adding dynamic shading control to the house had no significant effect on the loads or the rosette if shading was provided with internal Venetian blinds. The house as simulated had no external shading features. Addition of external shading features will change both the loads and the rosettes. Different types of external shading control should be examined.

One method controlling the conditions within a house is to add thermal mass. Most of the houses in this study are well insulated, but do not have a great deal of thermal mass in their construction. Adding thermal mass to the house may change the magnitude of the loads, change the distribution of the load lines around the rosette, or both.

None of the houses simulated included a basement. Literature suggests that basements are one location in a house where moisture control is likely to become a problem, so the rosettes for a house with a basement could look quite different from those for the houses in this study. Since the basement is set up as a separate zone in ESP-r, the results may be best presented by two rosettes, one for the above ground zone and one for the basement zone. Comparing the rosettes for multiple zones might provide better guidance for specifying HVAC equipment.

Similarly, all of the houses in this study use a vaulted ceiling with no attic space. A more traditional vented attic may affect the results, depending on how the attic space is constructed.

Attached houses are becoming increasingly common in some areas, and present unique problems both for simulations and design. The construction of attached housing units (row houses, apartment buildings, condos) has implications for energy efficiency and air tightness. If the construction of an attached housing development uses extremely energy efficient building envelope construction, using the same equipment for all the units within the development may no longer be appropriate. Examining the rosettes for different units within an attached housing development would provide information on whether the location of a unit within a building or development should affect the choice of equipment.

Looking at attached housing opens up many factors for consideration that do not need to be considered with detached housing - the presence of adjacent units would affect the loads within the unit that is being simulated, but how the simulated unit would be affected is unknown. It is unknown whether the location of the adjacent unit would affect how much that adjacent unit would affect the unit in question, especially given that the walls between units are generally well insulated. Because so much is dependent on occupant behaviour many assumptions would need to be made, and the simulations would rapidly become extremely complex.

5.3.3 Moisture Generation

Research on moisture generation rates is very limited. This makes it difficult to add accurate latent loads to the occupancy schedules. Re-examining the results from the simulations, the moisture generation rates used were probably underestimated, but they provide a starting point for future research into moisture generation rates.

All of the houses in this study had high sensible cooling capacity incorporated into the equipment models. In reality, the sensible cooling equipment in a house may be limited, or there may not be any sensible cooling equipment at all. What happens to the rosette for the super-insulated house if the sensible cooling capacity is either limited or non-existent? How do the latent loads in the house change in this case, and what happens to the relative humidity in this house?

As a follow up to a simulation with no sensible cooling equipment within the house, the case of a house with no moisture control should be simulated. In this house, sensible cooling may or may not be available, but the relative humidity within the conditioned space will be allowed to free float. In this case, how frequently would the the RH within the house be outside of a range that is acceptable for thermal comfort?

Super House B uses increased sensible and latent gains within the house. This does not take into account the possibility of increased latent gains while the sensible gains are held constant. A simulation of the high efficiency house construction could be run with the same sensible gains as the base case, but with increasing moisture generation rates, to find the point at which the loads become dominated by dehumidification rather than humidification.

5.3.4 Detailed Model of Real House

The houses in this study are based on a small house that is not necessarily a typical house for the locations in which it was simulated. A logical next step to this research would be to model an occupied house in either the Kitchener-Waterloo area or in Toronto, including input from the occupants about their weekly schedules and habits. By changing these schedules, the effect of different activities on the sensible and latent loads could be estimated. This could also be done using the house that was modelled for this thesis, but by using a more realistic occupancy and internal gain schedule.

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APPENDICES

Appendix A

Occupancy and Casual Gain Schedules

A.1 Two Occupants

In ESP-r the occupancy and casual gains schedules are input as part of the operations file (.opr). Two operational files were created for the houses with two occupants in this study. Corresponding files were also created for the dummy zones to allow the HRV to be modelled. The first operations file was used for the 1970 house and did not include an HRV.

```
*Operations 2.1
*date Thu Jun 12 14:51:26 2014  # latest file modification
# operations of House defined in:
# ../zones/1970_House.opr
No HRV for house.
# control(no control of air flow  ), low mid & high setpoints
   0     0.000     0.000     0.000
     1   # number of flow periods in day type: weekdays
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.000    0    0.000
     1   # number of flow periods in day type: saturday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.000    0    0.000
     1   # number of flow periods in day type: sunday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.000    0    0.000
     1   # number of flow periods in day type: holiday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.000    0    0.000
*casual
no casual gain notes (yet)
# casual user-label type-key-word slot attributes
*type Occupancy    -                 1  0  0
*type Showers      NULNULNULNULNULNULNULNULNULNULNULNULNULNULNULNUL  2  0  0
*type Lights       -                 3  0  0
*type Other        NULNULNULNULNULNULNULNULNULNULNULNULNULNULNULNUL  5  0  0
*end_type
    23   # number of casual gains in day type: weekdays
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   5,    134.0,     78.8,  0.400,  0.600
   1,   5,   8,    151.5,     89.0,  0.400,  0.600
   1,   8,  17,      0.0,      0.0,  0.600,  0.400
   1,  17,  21,    151.5,     89.0,  0.400,  0.600
   1,  21,  24,    134.0,     78.8,  0.400,  0.600
   2,   0,   6,      0.0,      0.0,  0.300,  0.700
   2,   6,   7,     30.0,     15.0,  0.500,  0.500
   2,   7,  21,      0.0,      0.0,  0.300,  0.700
   2,  21,  22,     30.0,     15.0,  0.500,  0.500
   2,  22,  24,      0.0,      0.0,  0.300,  0.700
   3,   0,   5,      0.0,      0.0,  0.400,  0.600
   3,   5,   8,    250.0,      0.0,  0.300,  0.700
   3,   8,  17,      0.0,      0.0,  0.400,  0.600
   3,  17,  21,    250.0,      0.0,  0.300,  0.700
   3,  21,  24,    100.0,      0.0,  0.300,  0.700
   5,   0,   5,    400.0,      0.0,  0.500,  0.500
   5,   5,   6,    800.0,     15.0,  0.500,  0.500
   5,   6,   7,   3050.0,     35.0,  0.500,  0.500
   5,   7,   8,    800.0,     15.0,  0.500,  0.500
   5,   8,  17,    400.0,      0.0,  0.500,  0.500
   5,  17,  18,   3250.0,     35.0,  0.500,  0.500
   5,  18,  21,   1000.0,     15.0,  0.500,  0.500
   5,  21,  24,    800.0,     10.0,  0.500,  0.500
    17   # number of casual gains in day type: saturday
```

```
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,    134.0,     78.8,  0.400,  0.600
   1,   8,  21,    151.5,     89.0,  0.400,  0.600
   1,  21,  24,    134.0,     78.8,  0.400,  0.600
   2,   0,   8,      0.0,      0.0,  0.300,  0.700
   2,   8,   9,     30.0,     15.0,  0.500,  0.500
   2,   9,  24,      0.0,      0.0,  0.300,  0.700
   3,   0,   8,      0.0,      0.0,  0.400,  0.600
   3,   8,  17,    100.0,      0.0,  0.300,  0.700
   3,  17,  21,    250.0,      0.0,  0.300,  0.700
   3,  21,  24,      0.0,      0.0,  0.400,  0.600
   5,   0,   5,    400.0,      0.0,  0.500,  0.500
   5,   5,   7,    600.0,     15.0,  0.500,  0.500
   5,   7,   8,   2850.0,     35.0,  0.500,  0.500
   5,   8,  17,   1000.0,     20.0,  0.500,  0.500
   5,  17,  18,   3250.0,     15.0,  0.500,  0.500
   5,  18,  21,   1000.0,     15.0,  0.500,  0.500
   5,  21,  24,    800.0,     10.0,  0.500,  0.500
    17   # number of casual gains in day type: sunday
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,    134.0,     78.8,  0.400,  0.600
   1,   8,  21,    151.5,     89.0,  0.400,  0.600
   1,  21,  24,    134.0,     78.8,  0.400,  0.600
   2,   0,   7,      0.0,      0.0,  0.300,  0.700
   2,   7,   8,     30.0,     15.0,  0.500,  0.500
   2,   8,  24,      0.0,      0.0,  0.300,  0.700
   3,   0,   8,      0.0,      0.0,  0.400,  0.600
   3,   8,  17,    100.0,      0.0,  0.400,  0.600
   3,  17,  21,    250.0,      0.0,  0.400,  0.600
   3,  21,  24,    100.0,      0.0,  0.400,  0.600
   5,   0,   5,    400.0,      0.0,  0.500,  0.500
   5,   5,   7,    600.0,     15.0,  0.500,  0.500
   5,   7,   8,   2850.0,     35.0,  0.500,  0.500
   5,   8,  17,   1000.0,     20.0,  0.500,  0.500
   5,  17,  18,   3250.0,     35.0,  0.500,  0.500
   5,  18,  21,   1000.0,     15.0,  0.500,  0.500
   5,  21,  24,    800.0,     10.0,  0.500,  0.500
    17   # number of casual gains in day type: holiday
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,    134.0,     78.8,  0.400,  0.600
   1,   8,  21,    151.5,     89.0,  0.400,  0.600
   1,  21,  24,    134.0,     78.8,  0.400,  0.600
   2,   0,   7,      0.0,      0.0,  0.300,  0.700
   2,   7,   8,     30.0,     15.0,  0.500,  0.500
   2,   8,  24,      0.0,      0.0,  0.300,  0.700
   3,   0,   8,      0.0,      0.0,  0.400,  0.600
   3,   8,  17,    100.0,      0.0,  0.400,  0.600
   3,  17,  21,    250.0,      0.0,  0.400,  0.600
   3,  21,  24,    100.0,      0.0,  0.400,  0.600
   5,   0,   5,    400.0,      0.0,  0.500,  0.500
   5,   5,   7,    600.0,     15.0,  0.500,  0.500
   5,   7,   8,   2850.0,     35.0,  0.500,  0.500
   5,   8,  17,   1000.0,     20.0,  0.500,  0.500
```

```
   5,  17,  18,   3250.0,     35.0,  0.500,  0.500
   5,  18,  21,   1000.0,     15.0,  0.500,  0.500
   5,  21,  24,    800.0,     10.0,  0.500,  0.500
```

The second house operations file was used for the 2006 house and all the Super houses with two occupants, and does include an HRV.

```
*Operations 2.1
*date Fri Aug  1 11:30:55 2014  # latest file modification
# operations of House defined in:
# ../zones/Super_House.opr
No HRV for house.
# control(no control of air flow  ), low mid & high setpoints
   0     0.000     0.000     0.000
     1   # number of flow periods in day type: weekdays
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.274    2    0.000
     1   # number of flow periods in day type: saturday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.274    2    0.000
     1   # number of flow periods in day type: sunday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.274    2    0.000
     1   # number of flow periods in day type: holiday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.274    2    0.000
*casual
no casual gain notes (yet)
# casual user-label type-key-word slot attributes
*type Occupancy    -                 1  0  0
*type Showers      NULNULNULNULNULNULNULNULNULNULNULNULNULNULNULNUL  2  0  0
*type Lights       -                 3  0  0
*type Other        NULNULNULNULNULNULNULNULNULNULNULNULNULNULNULNUL  5  0  0
*end_type
    23   # number of casual gains in day type: weekdays
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   5,    134.0,     78.8,  0.400,  0.600
   1,   5,   8,    151.5,     89.0,  0.400,  0.600
   1,   8,  17,      0.0,      0.0,  0.600,  0.400
   1,  17,  21,    151.5,     89.0,  0.400,  0.600
   1,  21,  24,    134.0,     78.8,  0.400,  0.600
   2,   0,   6,      0.0,      0.0,  0.300,  0.700
   2,   6,   7,     30.0,     15.0,  0.500,  0.500
   2,   7,  21,      0.0,      0.0,  0.300,  0.700
   2,  21,  22,     30.0,     15.0,  0.500,  0.500
   2,  22,  24,      0.0,      0.0,  0.300,  0.700
   3,   0,   5,      0.0,      0.0,  0.400,  0.600
   3,   5,   8,    250.0,      0.0,  0.300,  0.700
   3,   8,  17,      0.0,      0.0,  0.400,  0.600
   3,  17,  21,    250.0,      0.0,  0.300,  0.700
   3,  21,  24,    100.0,      0.0,  0.300,  0.700
   5,   0,   5,    400.0,      0.0,  0.500,  0.500
   5,   5,   6,    800.0,     15.0,  0.500,  0.500
   5,   6,   7,   3050.0,     35.0,  0.500,  0.500
   5,   7,   8,    800.0,     15.0,  0.500,  0.500
   5,   8,  17,    400.0,      0.0,  0.500,  0.500
   5,  17,  18,   3250.0,     35.0,  0.500,  0.500
   5,  18,  21,   1000.0,     15.0,  0.500,  0.500
   5,  21,  24,    800.0,     10.0,  0.500,  0.500
    17   # number of casual gains in day type: saturday
```

```
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,    134.0,     78.8,  0.400,  0.600
   1,   8,  21,    151.5,     89.0,  0.400,  0.600
   1,  21,  24,    134.0,     78.8,  0.400,  0.600
   2,   0,   8,      0.0,      0.0,  0.300,  0.700
   2,   8,   9,     30.0,     15.0,  0.500,  0.500
   2,   9,  24,      0.0,      0.0,  0.300,  0.700
   3,   0,   8,      0.0,      0.0,  0.400,  0.600
   3,   8,  17,    100.0,      0.0,  0.300,  0.700
   3,  17,  21,    250.0,      0.0,  0.300,  0.700
   3,  21,  24,      0.0,      0.0,  0.400,  0.600
   5,   0,   5,    400.0,      0.0,  0.500,  0.500
   5,   5,   7,    600.0,     15.0,  0.500,  0.500
   5,   7,   8,   2850.0,     35.0,  0.500,  0.500
   5,   8,  17,   1000.0,     20.0,  0.500,  0.500
   5,  17,  18,   3250.0,     15.0,  0.500,  0.500
   5,  18,  21,   1000.0,     15.0,  0.500,  0.500
   5,  21,  24,    800.0,     10.0,  0.500,  0.500
    17   # number of casual gains in day type: sunday
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,    134.0,     78.8,  0.400,  0.600
   1,   8,  21,    151.5,     89.0,  0.400,  0.600
   1,  21,  24,    134.0,     78.8,  0.400,  0.600
   2,   0,   7,      0.0,      0.0,  0.300,  0.700
   2,   7,   8,     30.0,     15.0,  0.500,  0.500
   2,   8,  24,      0.0,      0.0,  0.300,  0.700
   3,   0,   8,      0.0,      0.0,  0.400,  0.600
   3,   8,  17,    100.0,      0.0,  0.400,  0.600
   3,  17,  21,    250.0,      0.0,  0.400,  0.600
   3,  21,  24,    100.0,      0.0,  0.400,  0.600
   5,   0,   5,    400.0,      0.0,  0.500,  0.500
   5,   5,   7,    600.0,     15.0,  0.500,  0.500
   5,   7,   8,   2850.0,     35.0,  0.500,  0.500
   5,   8,  17,   1000.0,     20.0,  0.500,  0.500
   5,  17,  18,   3250.0,     35.0,  0.500,  0.500
   5,  18,  21,   1000.0,     15.0,  0.500,  0.500
   5,  21,  24,    800.0,     10.0,  0.500,  0.500
    17   # number of casual gains in day type: holiday
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,    134.0,     78.8,  0.400,  0.600
   1,   8,  21,    151.5,     89.0,  0.400,  0.600
   1,  21,  24,    134.0,     78.8,  0.400,  0.600
   2,   0,   7,      0.0,      0.0,  0.300,  0.700
   2,   7,   8,     30.0,     15.0,  0.500,  0.500
   2,   8,  24,      0.0,      0.0,  0.300,  0.700
   3,   0,   8,      0.0,      0.0,  0.400,  0.600
   3,   8,  17,    100.0,      0.0,  0.400,  0.600
   3,  17,  21,    250.0,      0.0,  0.400,  0.600
   3,  21,  24,    100.0,      0.0,  0.400,  0.600
   5,   0,   5,    400.0,      0.0,  0.500,  0.500
   5,   5,   7,    600.0,     15.0,  0.500,  0.500
   5,   7,   8,   2850.0,     35.0,  0.500,  0.500
   5,   8,  17,   1000.0,     20.0,  0.500,  0.500
```

```
  5,  17,  18,   3250.0,     35.0,  0.500,  0.500
  5,  18,  21,   1000.0,     15.0,  0.500,  0.500
  5,  21,  24,    800.0,     10.0,  0.500,  0.500
```

A.2 Four Occupants

For Super House B, a new operations file was developed to account for the additional occupants.

```
*Operations 2.1
*date Tue Jul  8 15:59:23 2014  # latest file modification
# operations of House defined in:
# ../zones/Super_House_B.opr
No HRV for house.
# control(no control of air flow  ), low mid & high setpoints
   0     0.000     0.000     0.000
     1   # number of flow periods in day type: weekdays
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.274    2    0.000
     1   # number of flow periods in day type: saturday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.274    2    0.000
     1   # number of flow periods in day type: sunday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.274    2    0.000
     1   # number of flow periods in day type: holiday
# start, stop, infil, ventil, source, data
   0, 24,    0.000    0.274    2    0.000
*casual
no casual gain notes (yet)
# casual user-label type-key-word slot attributes
*type Occupancy    -                 1  0  0
*type Showers      NULNULNULNULNULNULNULNULNULNULNULNULNULNULNULNUL   2  0  0
*type Lights       -                 3  0  0
*end_type
    24   # number of casual gains in day type: weekdays
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   5,     268.1,     157.4,  0.400,  0.600
   1,   5,   8,     303.0,     178.0,  0.400,  0.600
   1,   8,  17,     151.5,      89.0,  0.400,  0.600
   1,  17,  21,     303.0,     178.0,  0.400,  0.600
   1,  21,  24,     268.1,     157.4,  0.400,  0.600
   2,   0,   6,       0.0,       0.0,  0.300,  0.700
   2,   6,   7,      60.0,      60.0,  0.500,  0.500
   2,   7,  21,       0.0,       0.0,  0.300,  0.700
   2,  21,  22,      60.0,      60.0,  0.500,  0.500
   2,  22,  24,       0.0,       0.0,  0.300,  0.700
   3,   0,   5,       0.0,       0.0,  0.400,  0.600
   3,   5,   8,     600.0,       0.0,  0.300,  0.700
   3,   8,  17,     300.0,       0.0,  0.300,  0.700
   3,  17,  21,     600.0,       0.0,  0.300,  0.700
   3,  21,  24,     200.0,       0.0,  0.300,  0.700
   5,   0,   5,     800.0,       0.0,  0.500,  0.500
   5,   5,   6,     900.0,      50.0,  0.500,  0.500
   5,   6,   7,    3460.0,     100.0,  0.500,  0.500
   5,   7,   8,     900.0,      50.0,  0.500,  0.500
   5,   8,  17,    1500.0,       0.0,  0.500,  0.500
   5,  17,  18,    4350.0,     100.0,  0.500,  0.500
   5,  18,  20,    1500.0,      35.0,  0.500,  0.500
   5,  20,  21,    2300.0,      65.0,  0.500,  0.500
   5,  21,  24,    1500.0,      25.0,  0.500,  0.500
    18   # number of casual gains in day type: saturday
```

```
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,     268.1,     157.4,  0.400,  0.600
   1,   8,  21,     303.0,     178.0,  0.400,  0.600
   1,  21,  24,     268.1,     157.4,  0.400,  0.600
   2,   0,   8,       0.0,       0.0,  0.300,  0.700
   2,   8,   9,      60.0,      60.0,  0.500,  0.500
   2,   9,  24,       0.0,       0.0,  0.300,  0.700
   3,   0,   5,       0.0,       0.0,  0.400,  0.600
   3,   5,   8,     200.0,       0.0,  0.300,  0.700
   3,   8,  17,     600.0,       0.0,  0.300,  0.700
   3,  17,  21,     800.0,       0.0,  0.300,  0.700
   3,  21,  24,     200.0,       0.0,  0.300,  0.700
   5,   0,   7,     800.0,       0.0,  0.500,  0.500
   5,   7,   8,    3400.0,      65.0,  0.500,  0.500
   5,   8,  17,    1500.0,      30.0,  0.500,  0.500
   5,  17,  18,    4350.0,      80.0,  0.500,  0.500
   5,  18,  20,    1850.0,      20.0,  0.500,  0.500
   5,  20,  21,    2650.0,      50.0,  0.500,  0.500
   5,  21,  24,    1500.0,      15.0,  0.500,  0.500
    18   # number of casual gains in day type: sunday
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,     268.1,     157.4,  0.400,  0.600
   1,   8,  21,     303.0,     178.0,  0.400,  0.600
   1,  21,  24,     268.1,     157.4,  0.400,  0.600
   2,   0,   7,       0.0,       0.0,  0.300,  0.700
   2,   7,   8,      60.0,      60.0,  0.500,  0.500
   2,   8,  24,       0.0,       0.0,  0.300,  0.700
   3,   0,   5,       0.0,       0.0,  0.400,  0.600
   3,   5,   8,     200.0,       0.0,  0.500,  0.500
   3,   8,  17,     600.0,       0.0,  0.300,  0.700
   3,  17,  21,     800.0,       0.0,  0.300,  0.700
   3,  21,  24,     200.0,       0.0,  0.300,  0.700
   5,   0,   7,     800.0,       0.0,  0.500,  0.500
   5,   7,   8,    3400.0,      65.0,  0.500,  0.500
   5,   8,  17,    1500.0,      30.0,  0.500,  0.500
   5,  17,  18,    4350.0,      80.0,  0.500,  0.500
   5,  18,  20,    1850.0,      20.0,  0.500,  0.500
   5,  20,  21,    2650.0,      50.0,  0.500,  0.500
   5,  21,  24,    1500.0,      15.0,  0.500,  0.500
    18   # number of casual gains in day type: holiday
# slot, period, sensible, latent, rad_frac, conv_frac
   1,   0,   8,     268.1,     157.4,  0.400,  0.600
   1,   8,  21,     303.0,     178.0,  0.400,  0.600
   1,  21,  24,     268.1,     157.4,  0.400,  0.600
   2,   0,   7,       0.0,       0.0,  0.300,  0.700
   2,   7,   8,      60.0,      60.0,  0.500,  0.500
   2,   8,  24,       0.0,       0.0,  0.300,  0.700
   3,   0,   5,       0.0,       0.0,  0.400,  0.600
   3,   5,   8,     200.0,       0.0,  0.300,  0.700
   3,   8,  17,     600.0,       0.0,  0.300,  0.700
   3,  17,  21,     800.0,       0.0,  0.300,  0.700
   3,  21,  24,     200.0,       0.0,  0.300,  0.700
   5,   0,   7,     800.0,       0.0,  0.500,  0.500
```

```
  5,   7,   8,   3400.0,     65.0,  0.500,  0.500
  5,   8,  17,   1500.0,     30.0,  0.500,  0.500
  5,  17,  18,   4350.0,     80.0,  0.500,  0.500
  5,  18,  20,   1850.0,     20.0,  0.500,  0.500
  5,  20,  21,   2650.0,     50.0,  0.500,  0.500
  5,  21,  24,   1500.0,     15.0,  0.500,  0.500
```

A.3 Infiltration

Three AIM-2 input files were created for this study, one for the 1970 house, one for the 2006 house, and one that was used with the Super house construction.

```
#---Leakage description-------------------------------------------------------------------------
1   6.68  10.00 1  616.10   0.61       # Blower door input;   6.68ac/h @50 Pa; ELA dP=10.00 Pa;
ELA=616.10 cm^2; Cd=0.61
#---Leakage distribution------------------------------------------------------------------------
0                           # Default leakage distribution.
#---Shielding and terrain data------------------------------------------------------------------
3 3 1 1 10.0                # Open flat terrain at weather station.
#                           # Building site terrain:Open flat terrain
#                           # Wall shielding:None.
#                           # No local shielding on flue.
#                           # Height of anemometer at weather station.
#---Height of building eaves (m)----------------------------------------------------------------
4
#---Flue diameters (mm)-------------------------------------------------------------------------
0  0. 0. 0. 0.              # furnace, fire#1, fire#2, dhw#1, dhw#2.
#---Zone indices--------------------------------------------------------------------------------
1                           # Zone whose temperature used to calculate density of indoor air.
1 1                         # Total number of zones receiving infil; indices of zones receive
infil.
0 0 0                       # Index of basement zone (=0 if no basement), crawlspace, and attic.
#-----------------------------------------------------------------------------------------------
```

```
#---Leakage description-------------------------------------------------------------------------
1   3.04  10  1  287.30   0.61       # Blower door input;   6.68ac/h @50 Pa; ELA dP=10.00 Pa;
ELA=616.10 cm^2; Cd=0.61
#---Leakage distribution------------------------------------------------------------------------
0                           # Default leakage distribution.
#---Shielding and terrain data------------------------------------------------------------------
3 3 1 1 10.0                # Open flat terrain at weather station.
#                           # Building site terrain:Open flat terrain
#                           # Wall shielding:None.
#                           # No local shielding on flue.
#                           # Height of anemometer at weather station.
#---Height of building eaves (m)----------------------------------------------------------------
4
#---Flue diameters (mm)-------------------------------------------------------------------------
0  0. 0. 0. 0.              # furnace, fire#1, fire#2, dhw#1, dhw#2.
#---Zone indices--------------------------------------------------------------------------------
1                           # Zone whose temperature used to calculate density of indoor air.
1 1                         # Total number of zones receiving infil; indices of zones receive
infil.
0 0 0                       # Index of basement zone (=0 if no basement), crawlspace, and attic.
#-----------------------------------------------------------------------------------------------
```

```
#---Leakage description-------------------------------------------------------------------------
1   0.8  10  1  50   0.61       # Blower door input;   0.8ac/h @50 Pa; ELA dP=10.00 Pa; ELA=50
cm^2; Cd=0.61
#---Leakage distribution------------------------------------------------------------------------
0                            # Default leakage distribution.
#---Shielding and terrain data------------------------------------------------------------------
3 3 1 1 10.0                 # Open flat terrain at weather station.
#                            # Building site terrain:Open flat terrain
#                            # Wall shielding:None.
#                            # No local shielding on flue.
#                            # Height of anemometer at weather station.
#---Height of building eaves (m)----------------------------------------------------------------
4
#---Flue diameters (mm)-------------------------------------------------------------------------
0  0. 0. 0. 0.               # furnace, fire#1, fire#2, dhw#1, dhw#2.
#---Zone indices--------------------------------------------------------------------------------
1                            # Zone whose temperature used to calculate density of indoor air.
1 1                          # Total number of zones receiving infil; indices of zones receive
infil.
0 0 0                        # Index of basement zone (=0 if no basement), crawlspace, and attic.
#-----------------------------------------------------------------------------------------------
```

Appendix B

Typical Weeks for Alternate Locations

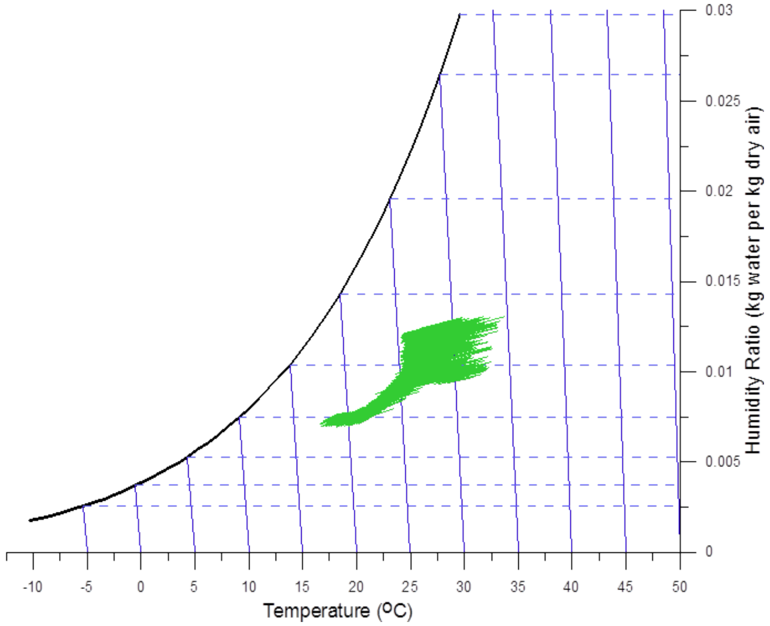
Because of the large number of plots that are generated for each simulation, the typical week plots for the simulations of the house in Whitehorse, Shearwater, Vancouver, and Winnipeg, are located in this appendix.

B.1 Winnipeg, Manitoba

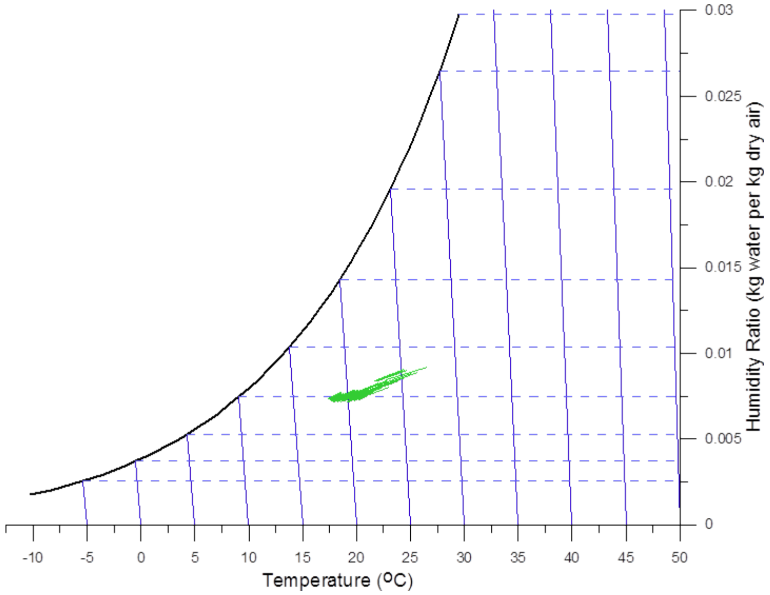
Typical weeks for Winnipeg are found using the utility in ESP-r to determine typical weeks in a given climate file. Inputs for finding the typical weeks are a heating base temperature of 21 °C and a cooling base temperature of 25 °C. ESP-r defaults were used for all other inputs required to find the typical weeks for the Winnipeg climate file.

Table B.1: Start and end dates for seasonal typical weeks using Winnipeg climate data

Season	**Typical Week Start (00h)**	**Typical Week End (24h)**
Winter 1	29 January	4 February
Spring	9 April	15 April
Summer	20 August	26 August
Fall	8 October	14 October
Winter 2	26 November	2 December

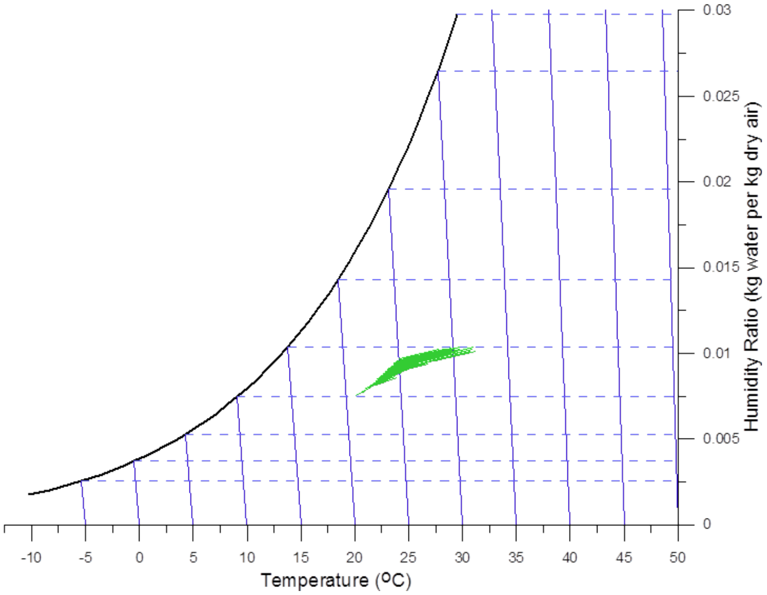


(a) Entire year

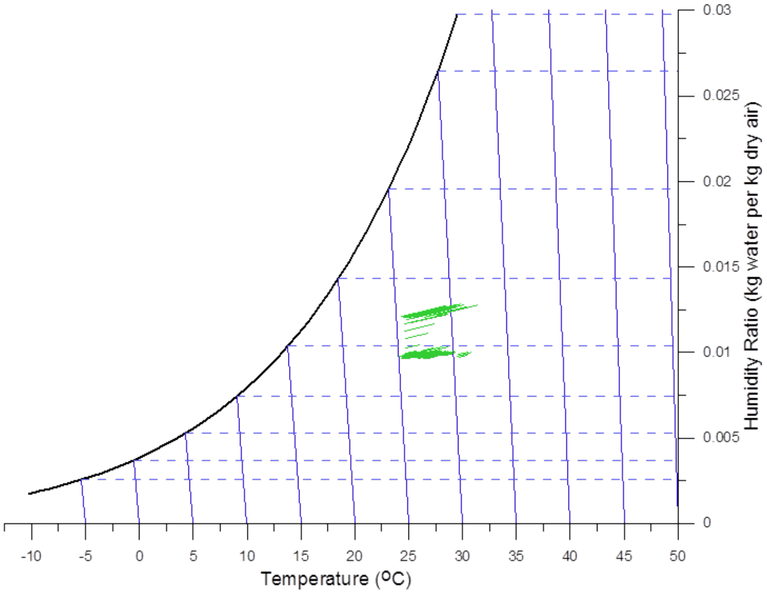


(b) Winter 1

Figure B.1: Results from simulation of Winnipeg house

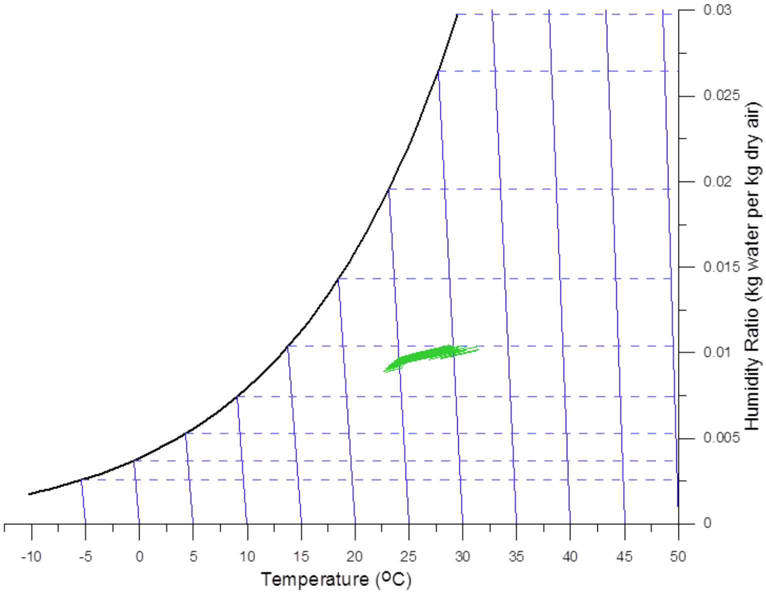


(c) Spring

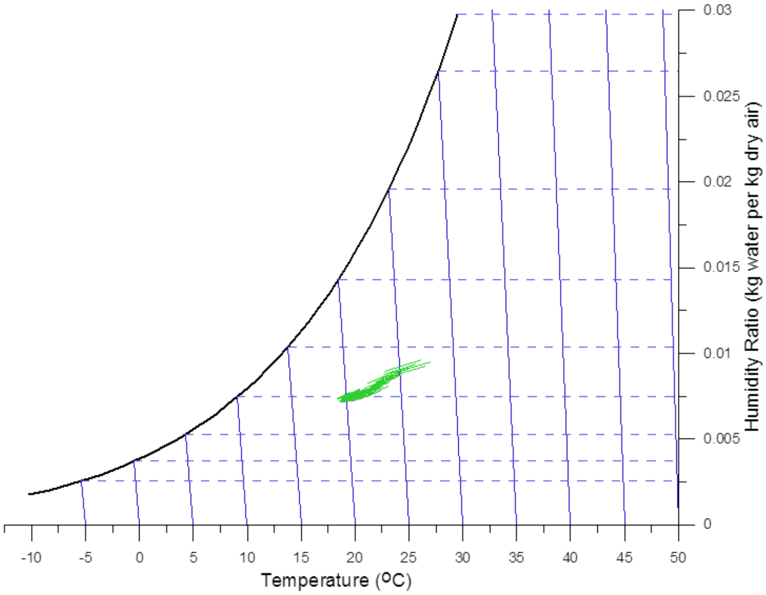


(d) Summer

Results from simulation of Winnipeg house

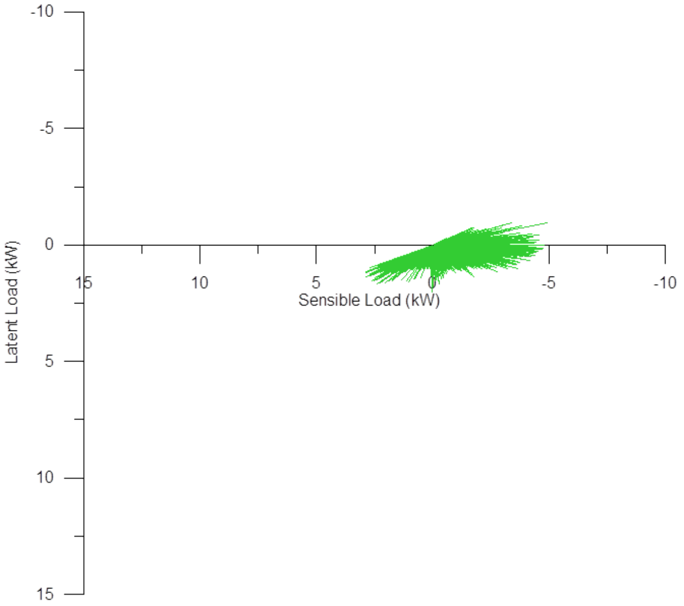


(e) Fall

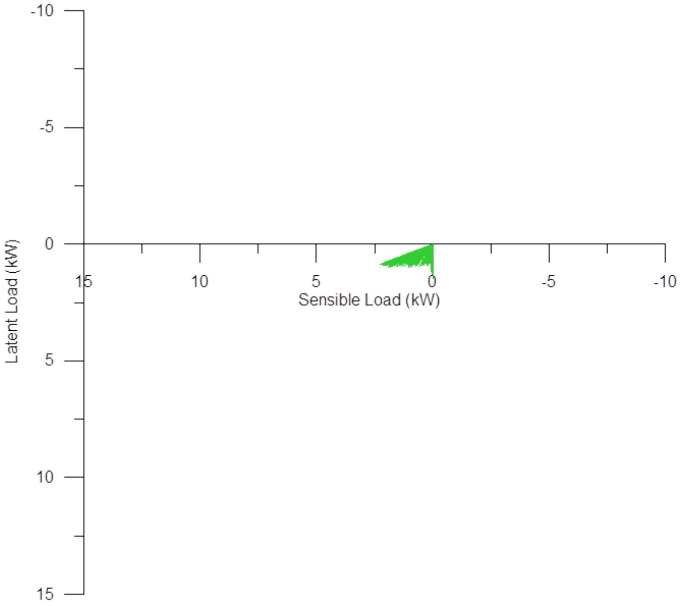


(f) Winter 2

Results from simulation of Winnipeg house

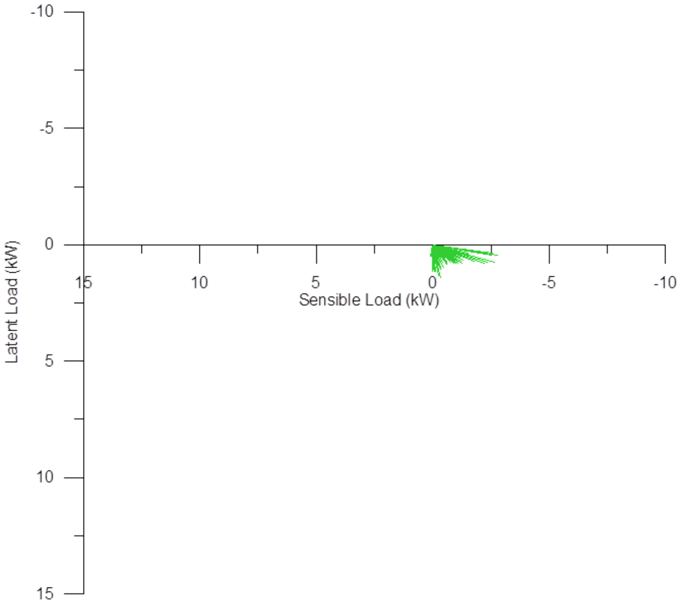


(a) Annual results

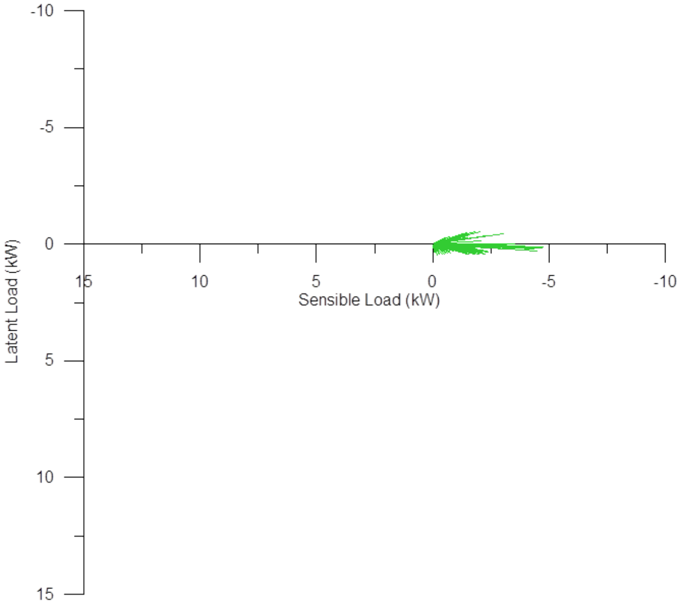


(b) Winter 1

Figure B.2: Results from simulation of Winnipeg house, single point plots

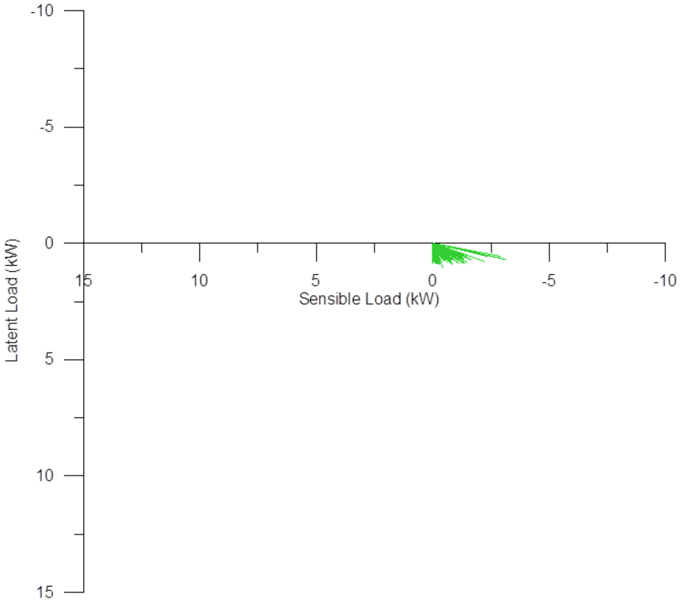


(c) Spring

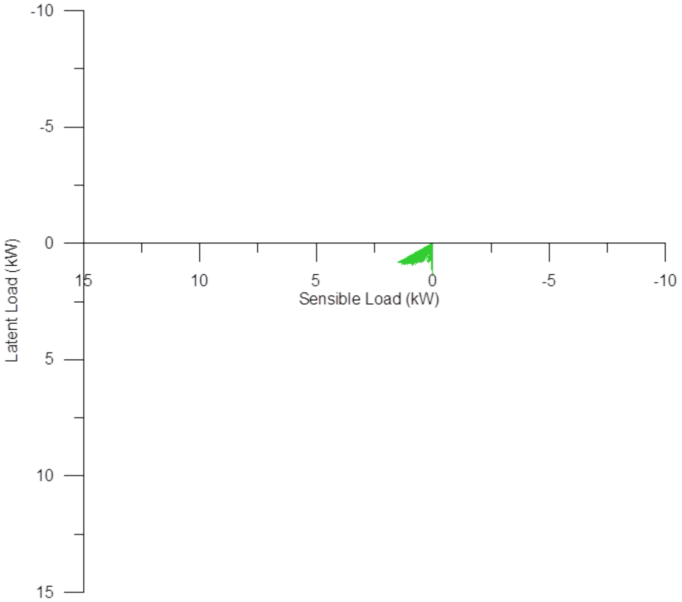


(d) Summer

Results from simulation of Winnipeg house, single point plots



(e) Fall



(f) Winter 2

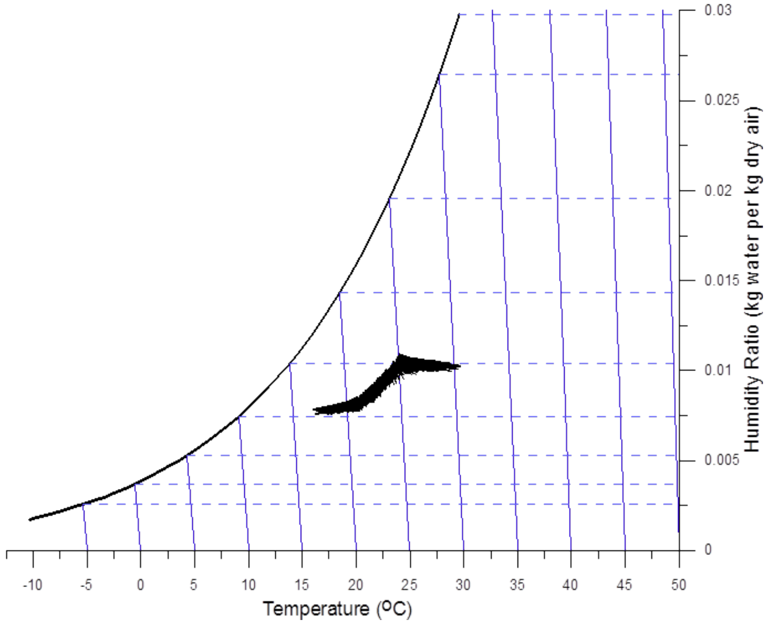
Results from simulation of Winnipeg house, single point plots

B.2 Whitehorse, Yukon Territory

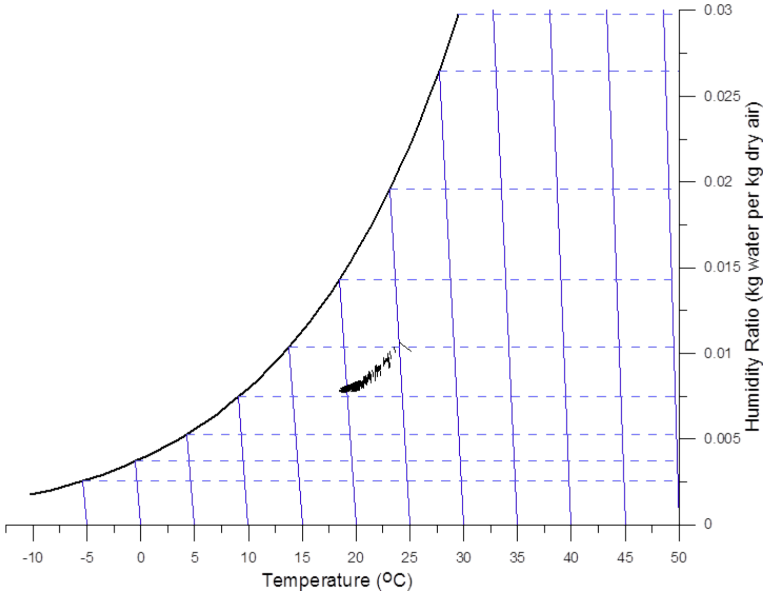
Typical weeks for Whitehorse are found using the utility in ESP-r. Inputs for finding the typical weeks are the same as those used for the Winnipeg climate file.

Table B.2: Start and end dates for seasonal typical weeks using Yukon climate data

Season	**Typical Week Start (00h)**	**Typical Week End (24h)**
Winter 1	19 February	25 February
Spring	30 April	6 May
Summer	23 July	29 July
Fall	24 September	30 September
Winter 2	26 November	2 December

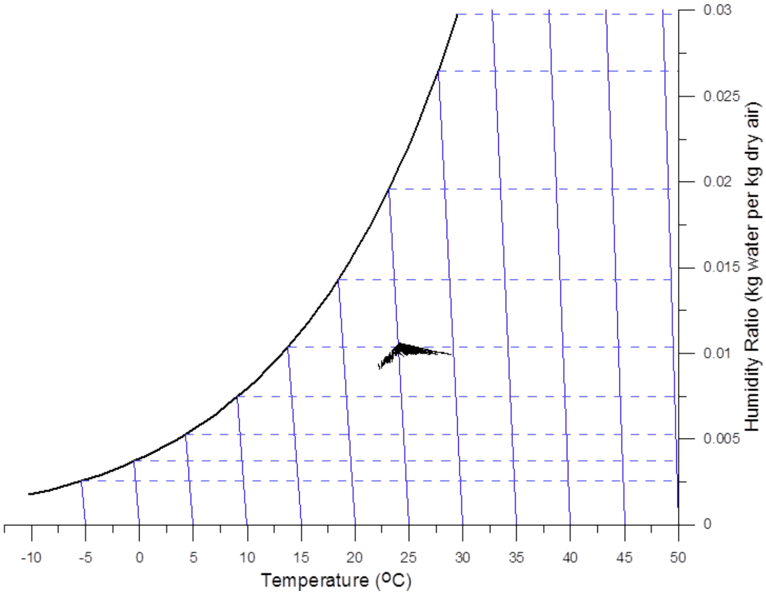


(a) Entire year

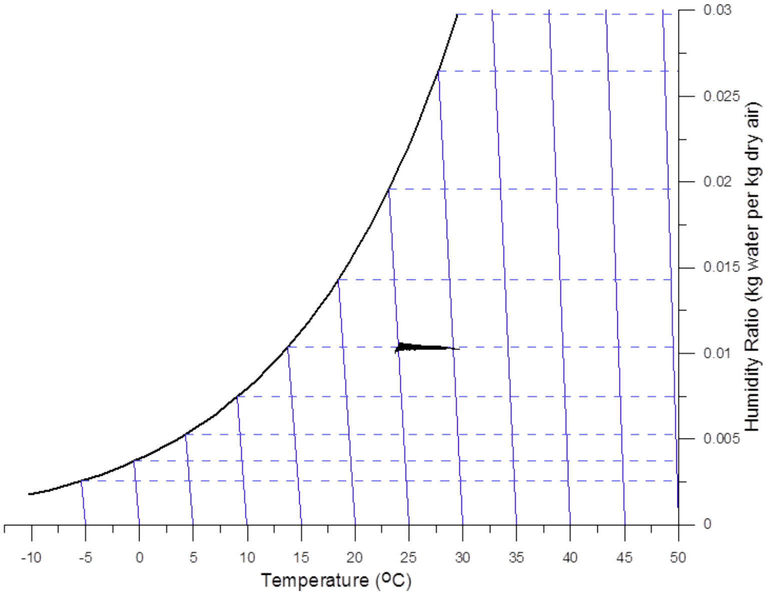


(b) Winter 1

Figure B.3: Results from simulation of Whitehorse house

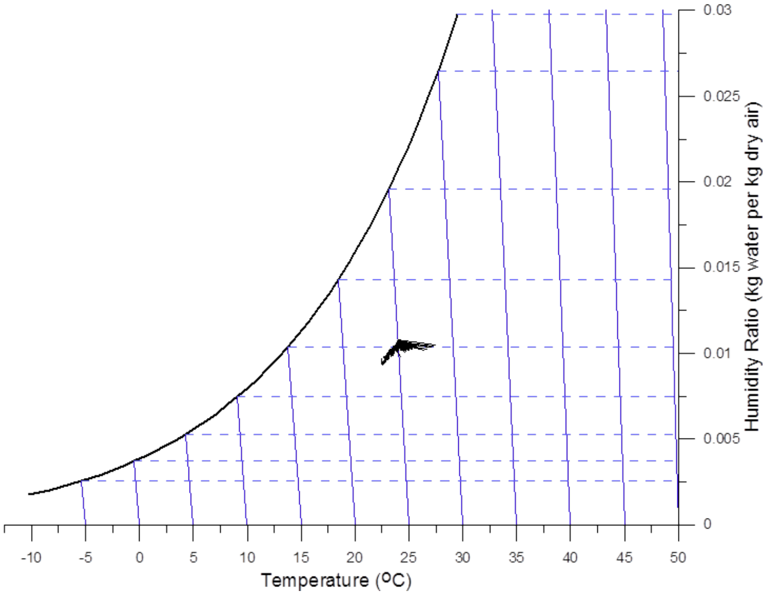


(c) Spring

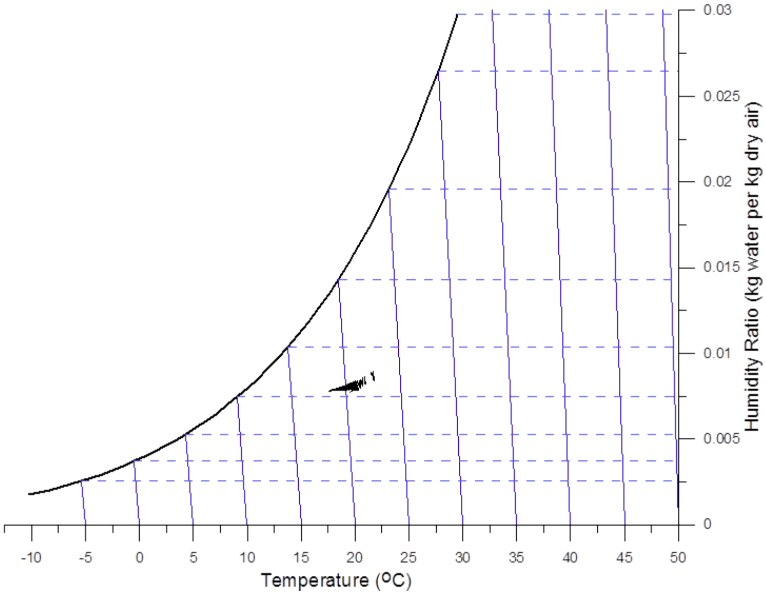


(d) Summer

Results from simulation of Whitehorse house

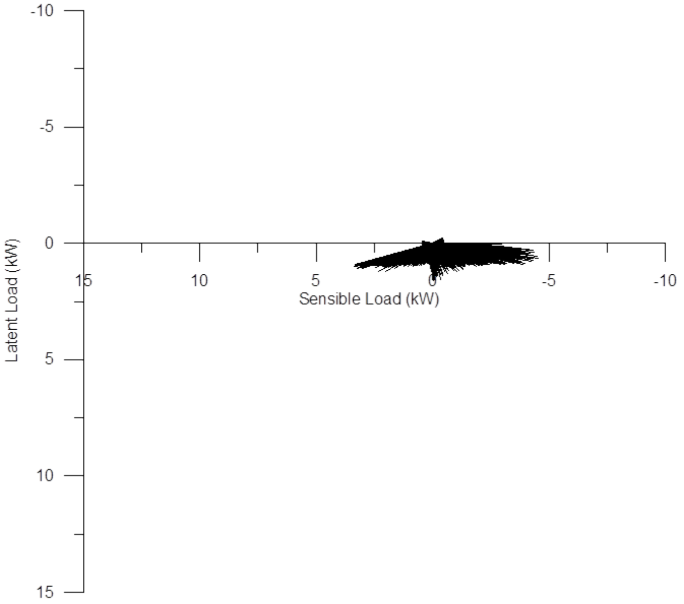


(e) Fall

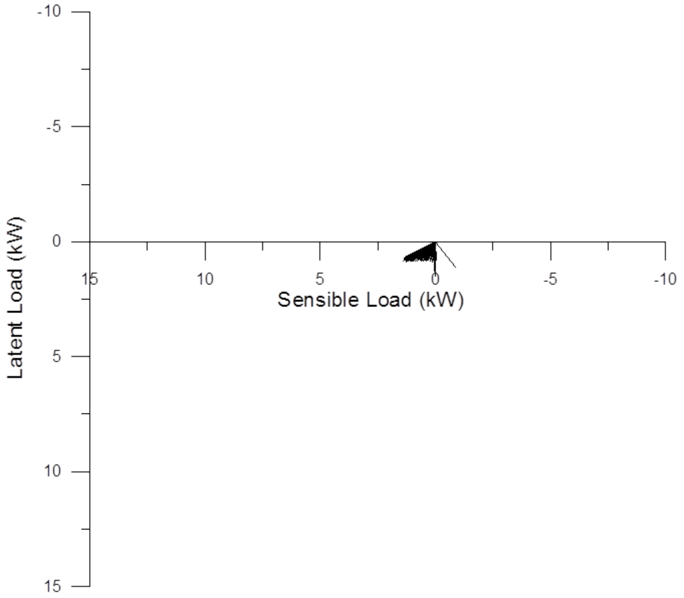


(f) Winter 2

Results from simulation of Whitehorse house

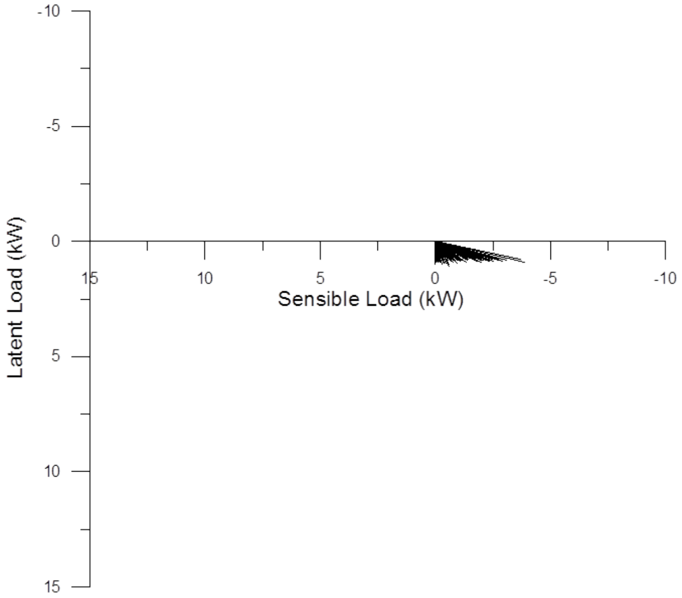


(a) Annual results

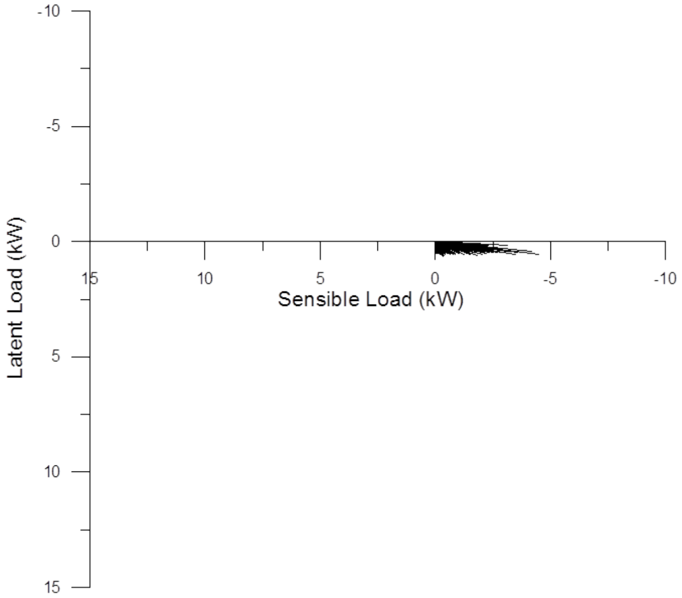


(b) Winter 1

Figure B.4: Results from simulation of Whitehorse house, single point plots

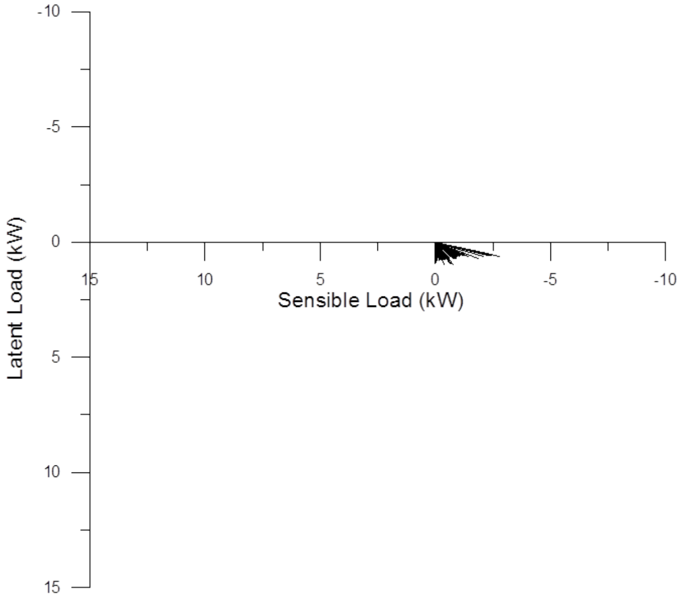


(c) Spring

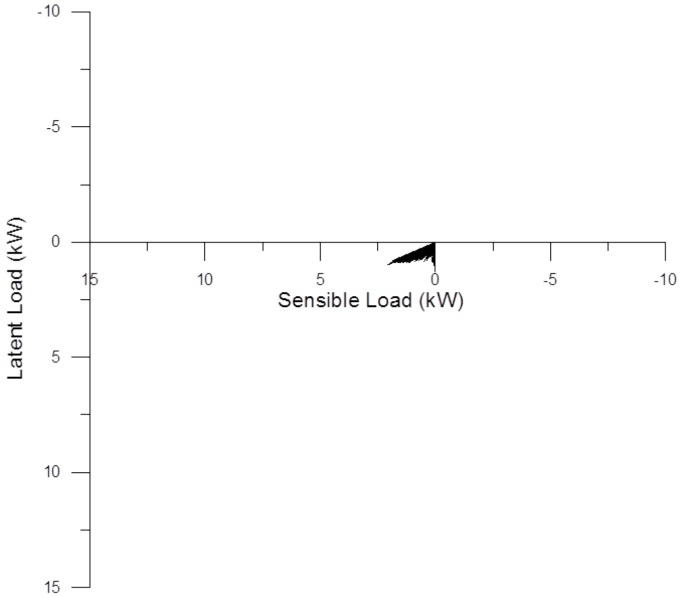


(d) Summer

Results from simulation of Whitehorse house, single point plots



(e) Fall



(f) Winter 2

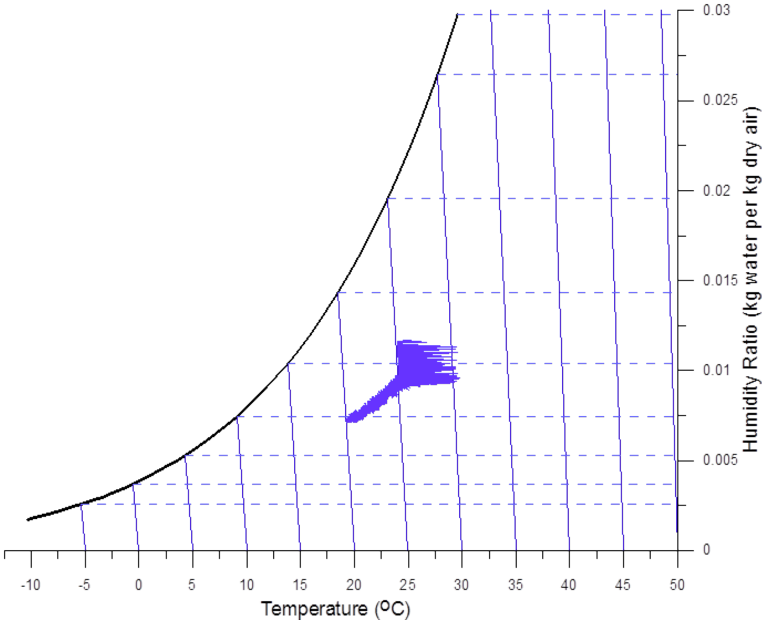
Results from simulation of Whitehorse house, single point plots

B.3 Vancouver, British Columbia

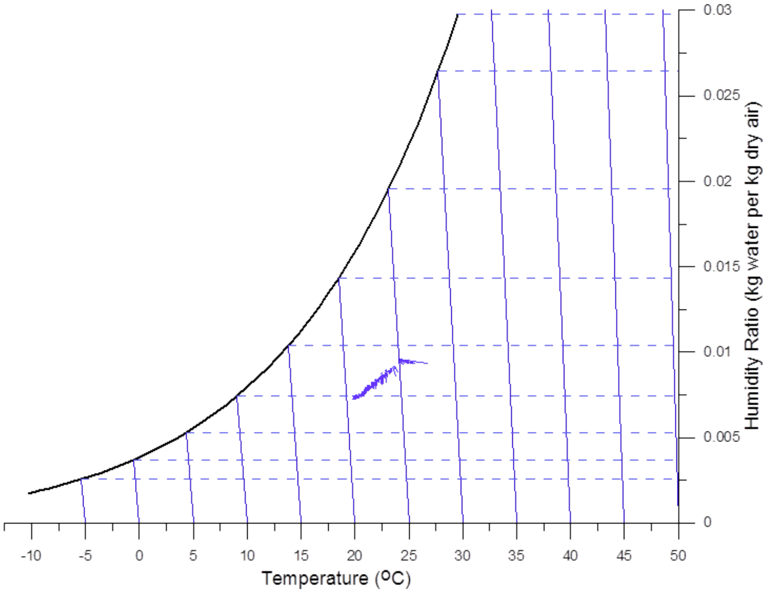
Typical weeks for Vancouver are found using the utility in ESP-r. Inputs for finding the typical weeks are identical to those used for the Winnipeg climate file.

Table B.3: Start and end dates for seasonal typical weeks using Vancouver climate data

Season	**Typical Week Start (00h)**	**Typical Week End (24h)**
Winter 1	29 January	4 February
Spring	2 April	8 April
Summer	25 June	1 July
Fall	8 October	14 October
Winter 2	24 December	30 December

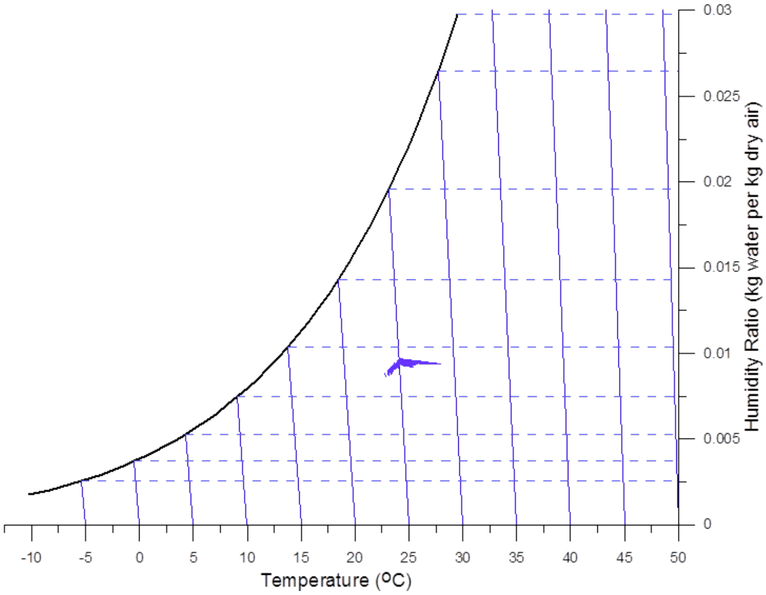


(a) Entire year

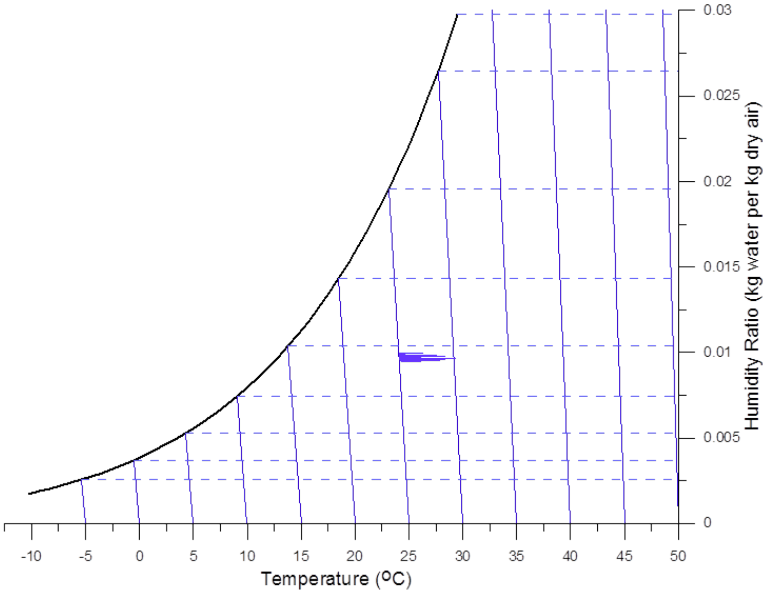


(b) Winter 1

Figure B.5: Results from simulation of Vancouver house

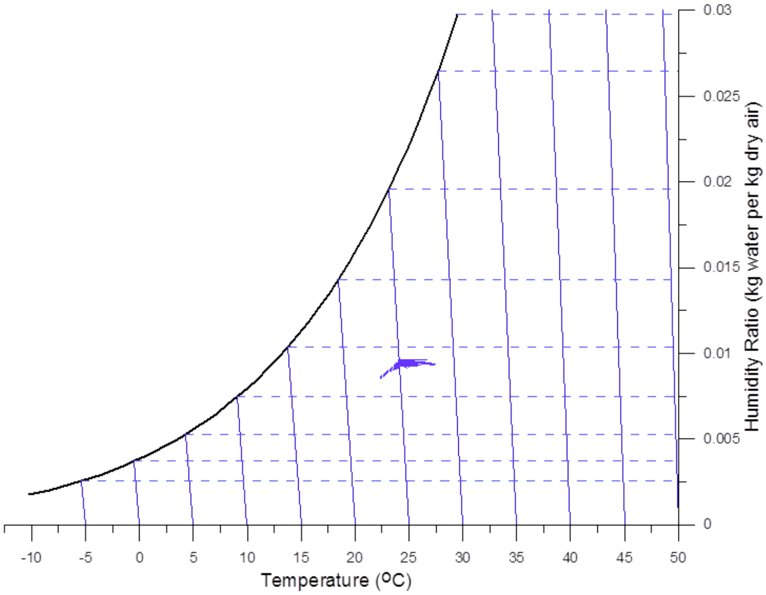


(c) Spring

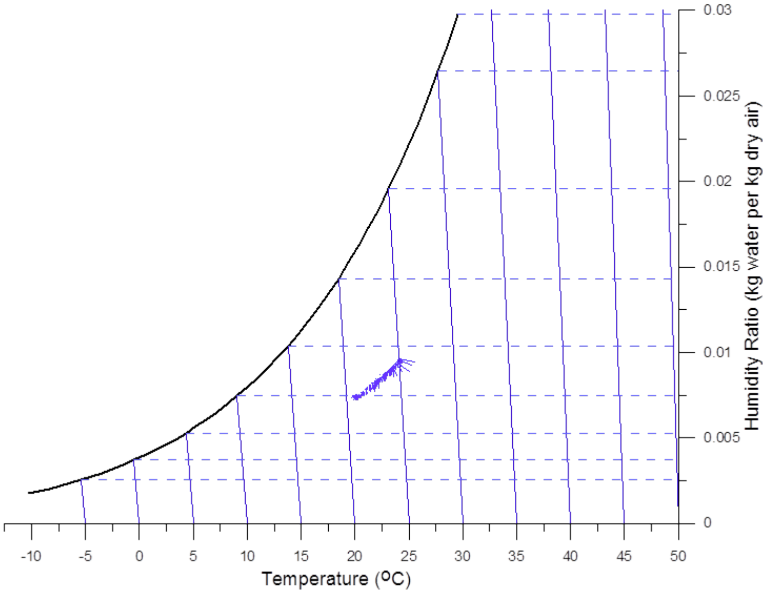


(d) Summer

Results from simulation of Vancouver house

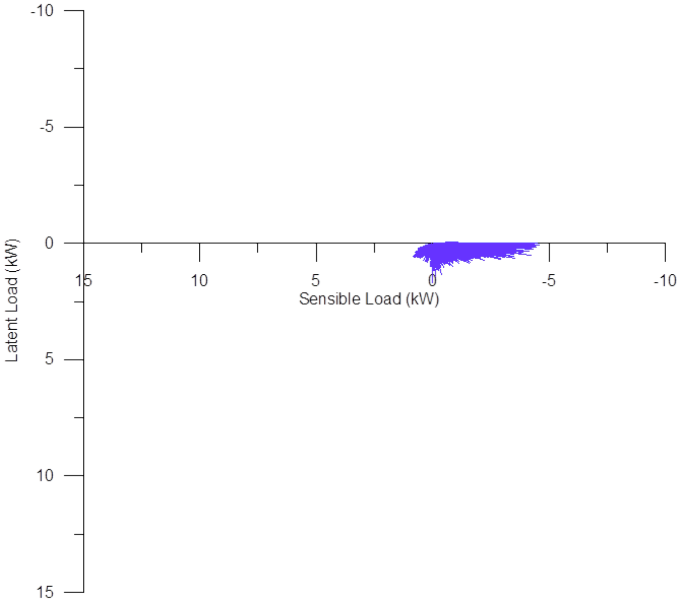


(e) Fall

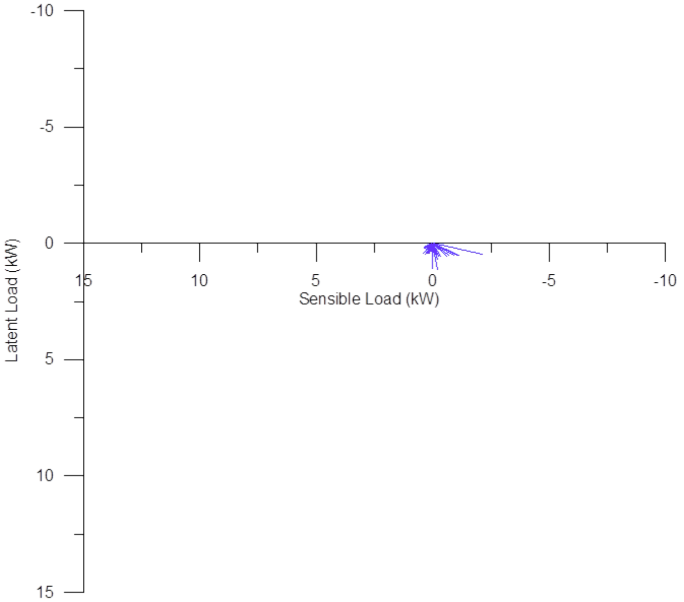


(f) Winter 2

Results from simulation of Vancouver house

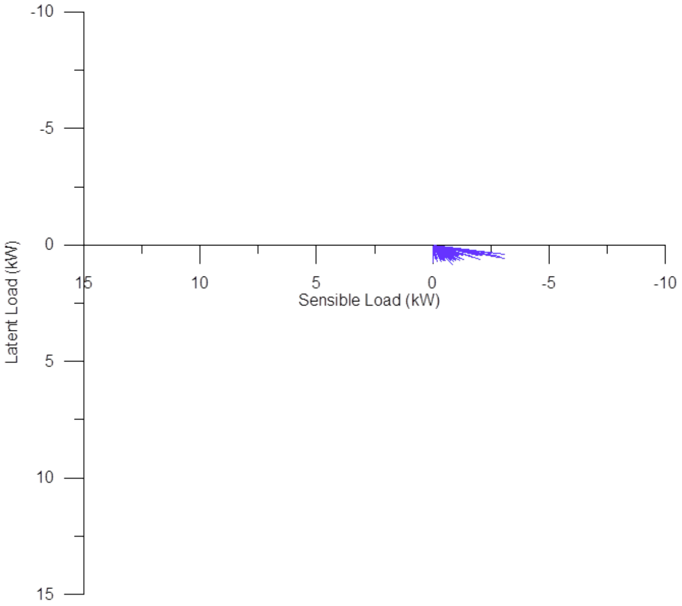


(a) Annual results

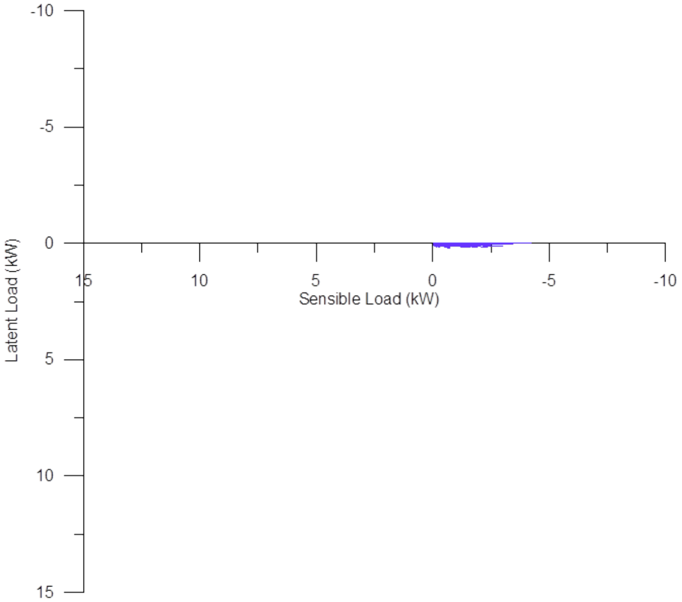


(b) Winter 1

Figure B.6: Results from simulation of Vancouver house, single point plots

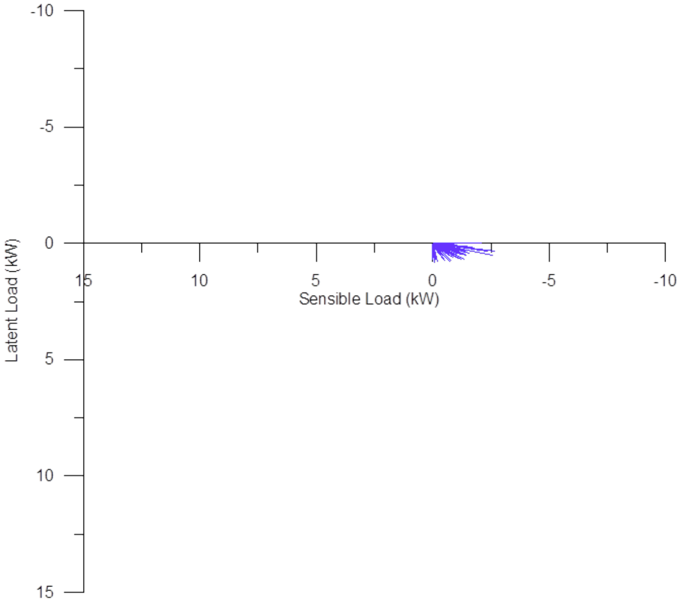


(c) Spring

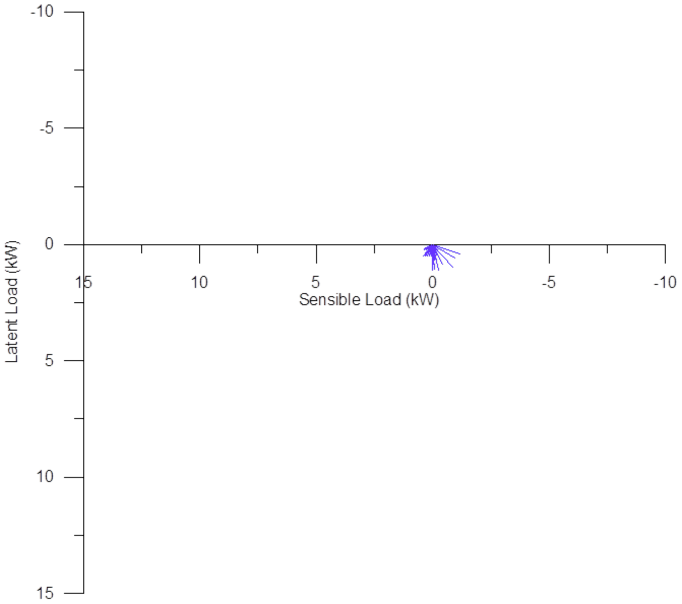


(d) Summer

Results from simulation of Vancouver house, single point plots



(e) Fall



(f) Winter 2

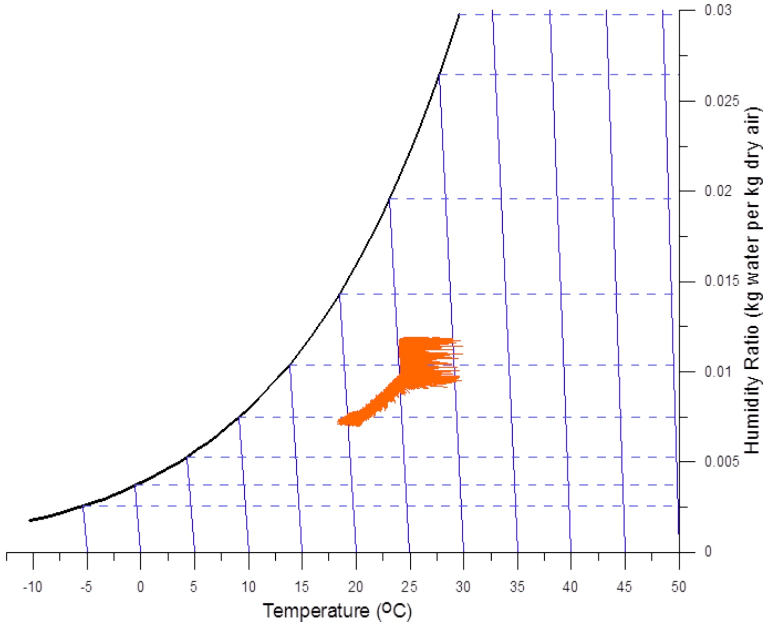
Results from simulation of Vancouver house, single point plots

B.4 Shearwater, Nova Scotia

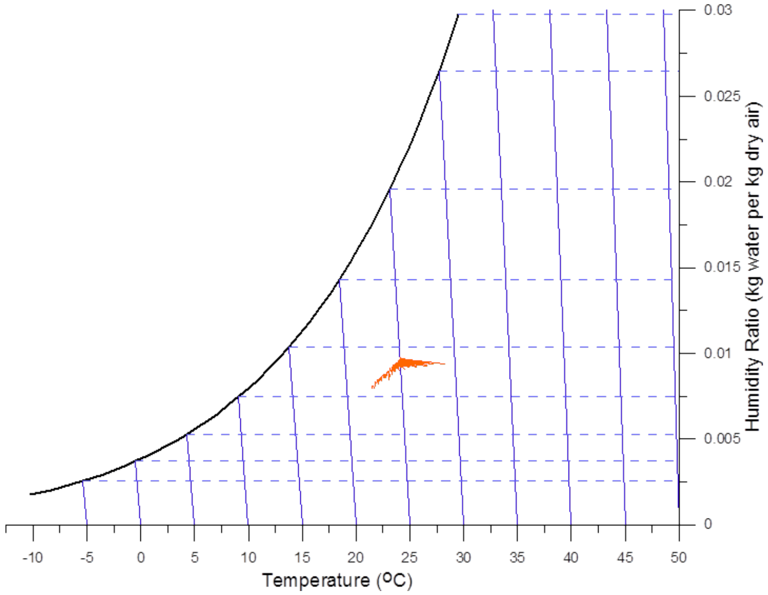
Typical weeks for Shearwater are found using the utility in ESP-r. Inputs for finding the typical weeks are the same as those used for the Winnipeg climate file.

Table B.4: Start and end dates for seasonal typical weeks using Shearwater climate data

Season	**Typical Week Start (00h)**	**Typical Week End (24h)**
Winter 1	19 February	25 February
Spring	30 April	6 May
Summer	9 July	15 July
Fall	1 October	7 October
Winter 2	19 November	25 November

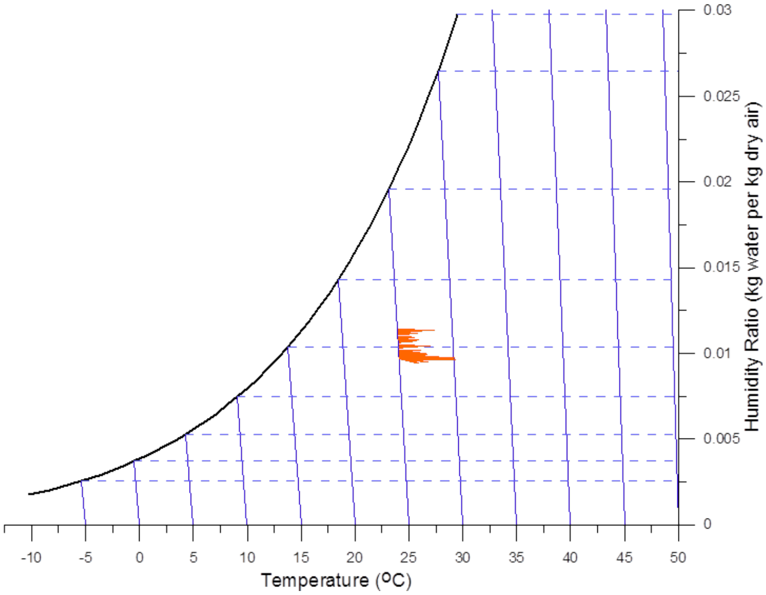


(a) Entire year

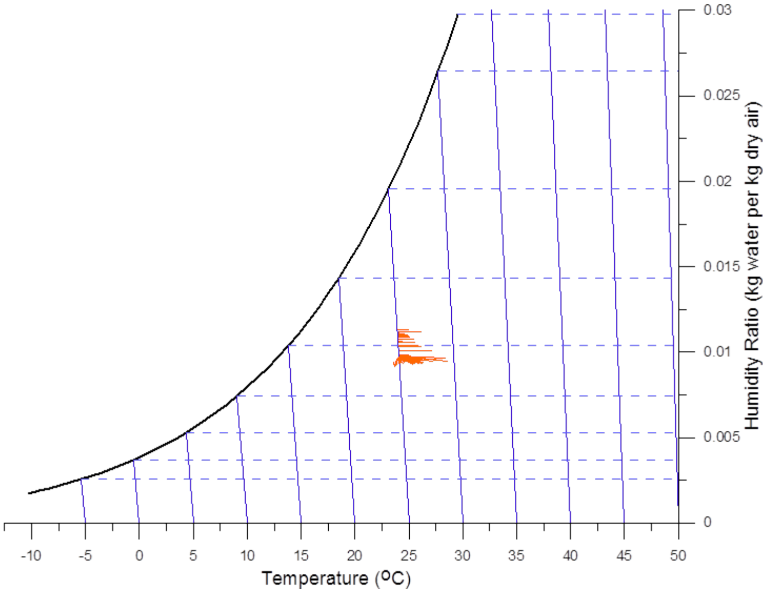


(b) Winter 1

Figure B.7: Results from simulation of Shearwater house

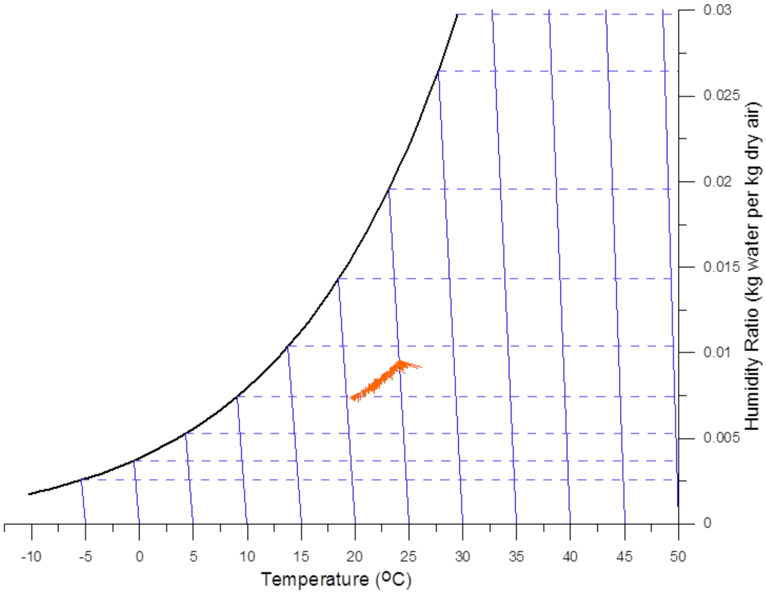


(c) Spring

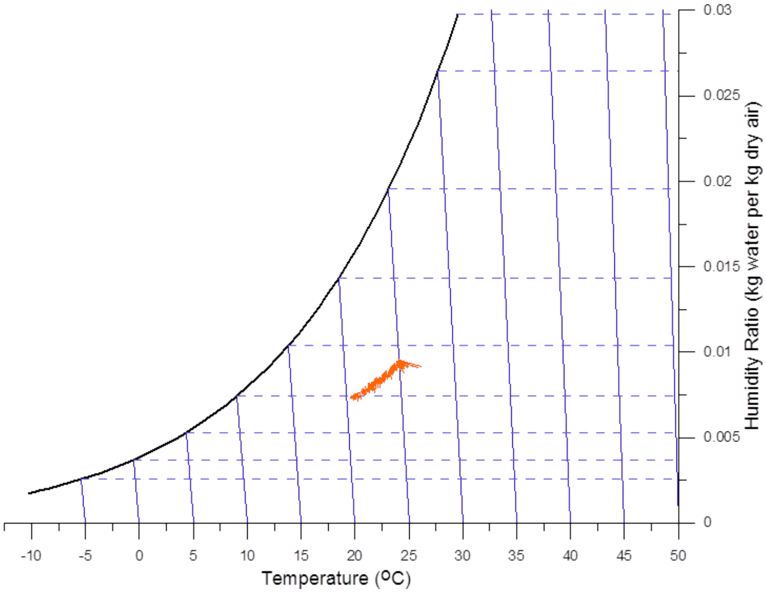


(d) Summer

Results from simulation of Shearwater house

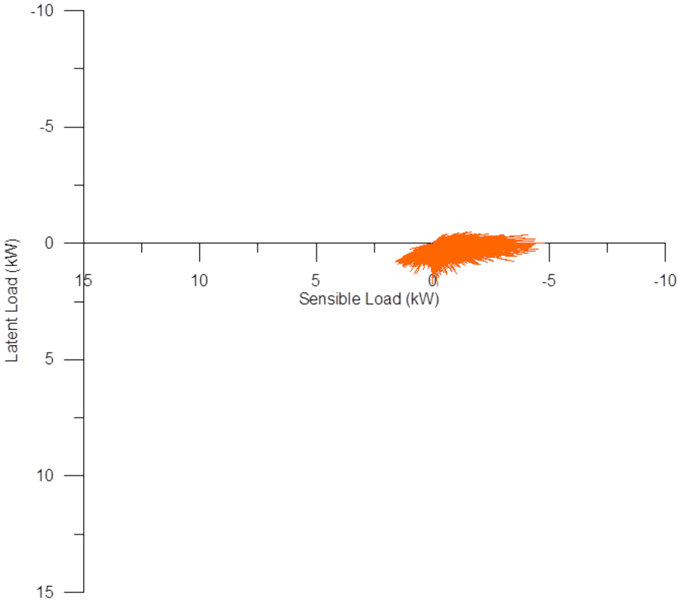


(e) Fall

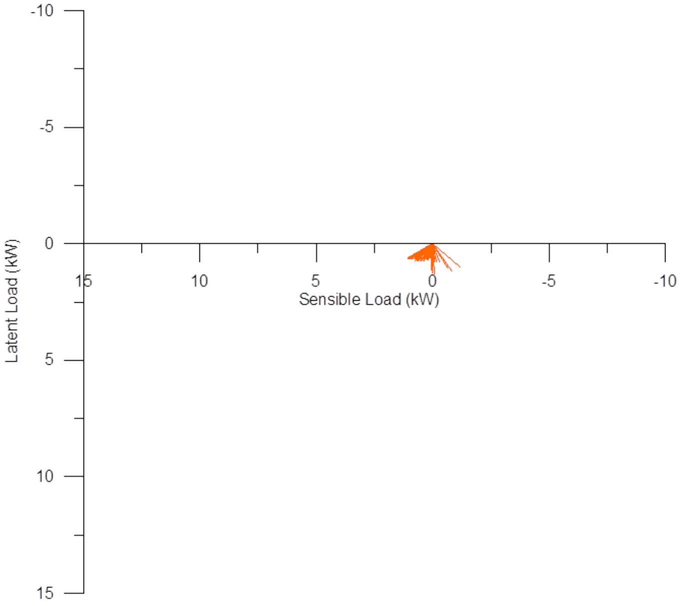


(f) Winter 2

Results from simulation of Shearwater house

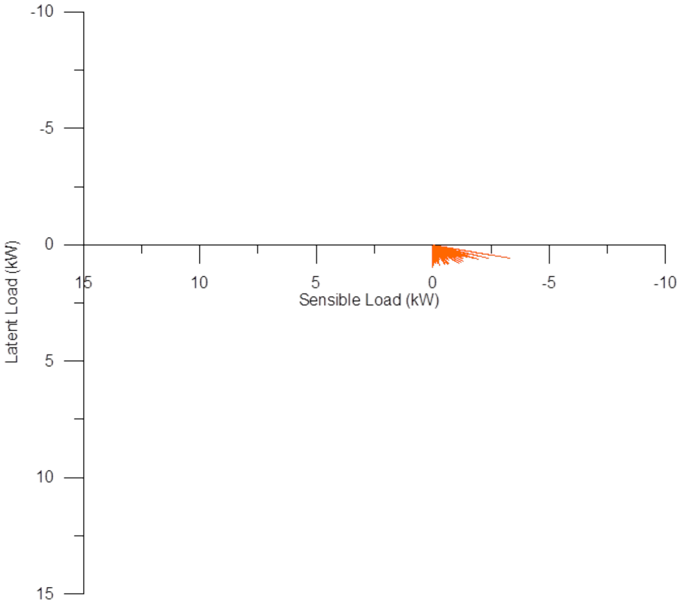


(a) Annual results

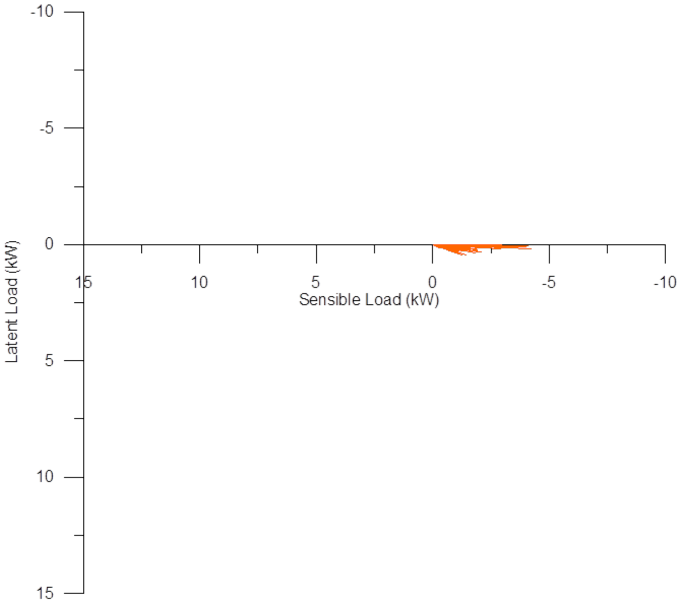


(b) Winter 1

Figure B.8: Results from simulation of Shearwater house, single point plots

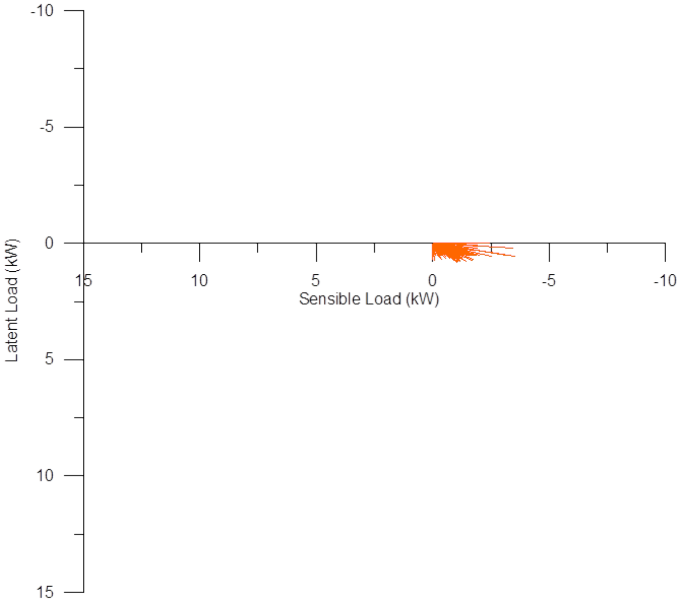


(c) Spring

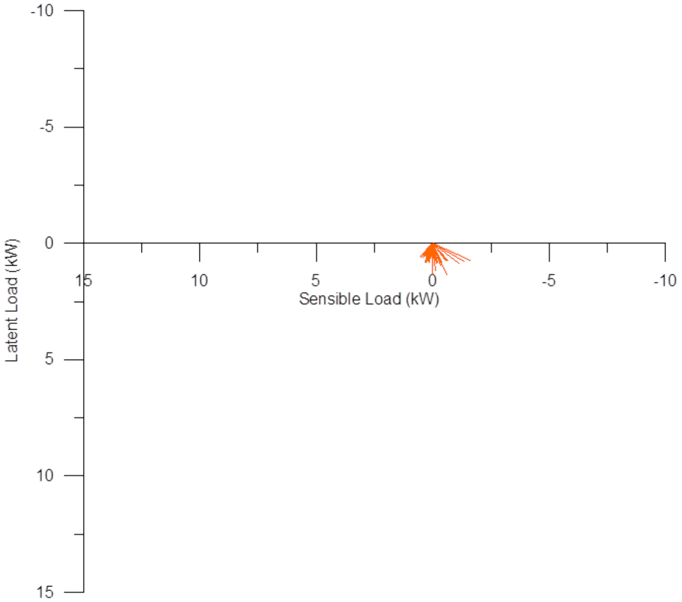


(d) Summer

Results from simulation of Shearwater house, single point plots



(e) Fall



(f) Winter 2

Results from simulation of Shearwater house, single point plots

Appendix C

Load Condition Frequency - Additional Plots

C.1 Group 1

This group consist of the 1970 house, the 2006 house, and Super House A. The first plot shows the frequency of sensible heating only, sensible cooling only, humidification only, and dehumidification only.

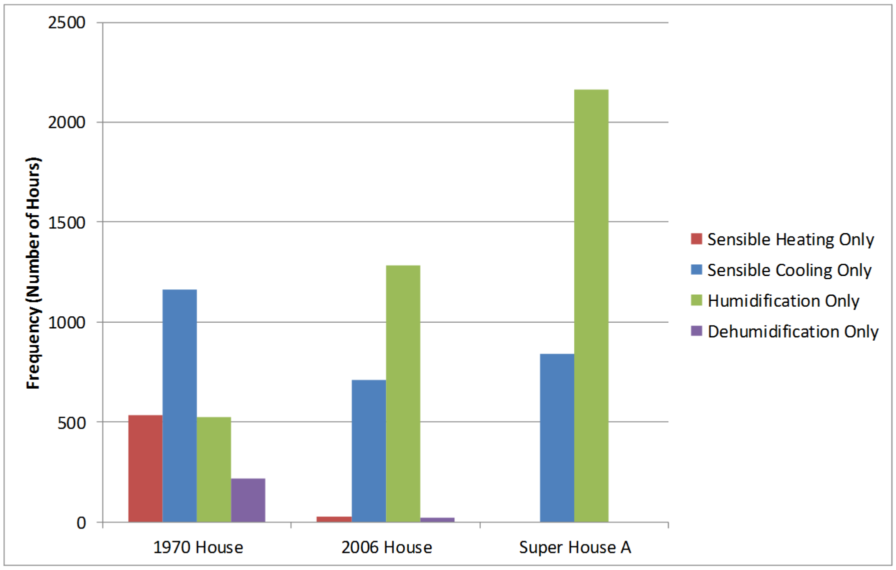


Figure C.1: Plot of load condition frequency for 1970's house, 2006 house, and Super House A,

The next plot shows four load combinations that can be expected within the house.

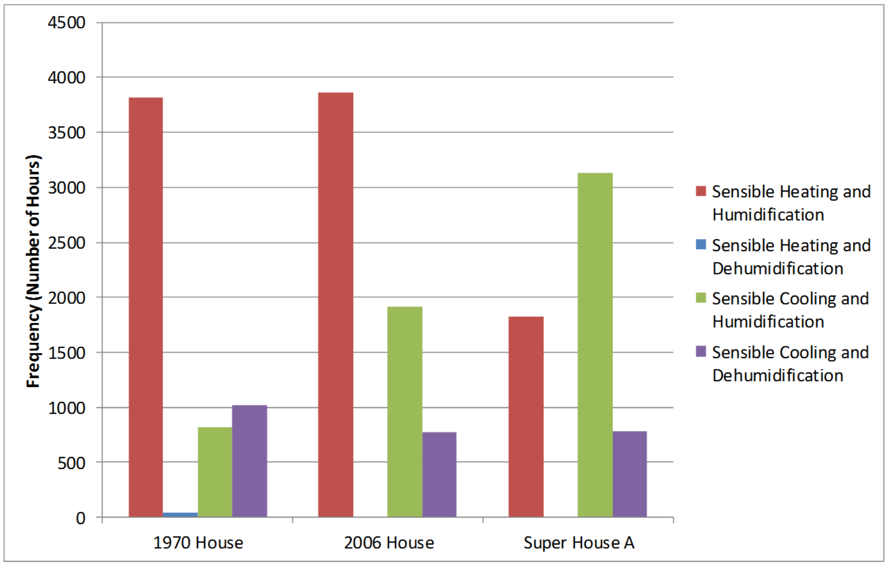


Figure C.2: Plot of load condition frequency for 1970's house, 2006 house, and Super House A

C.2 Group 2

This group consists of the Super Houses A, B, C, and D. As with the first group of houses examined, the first plot shows the frequency of sensible heating only, sensible cooling only, humidification only, and dehumidification only.

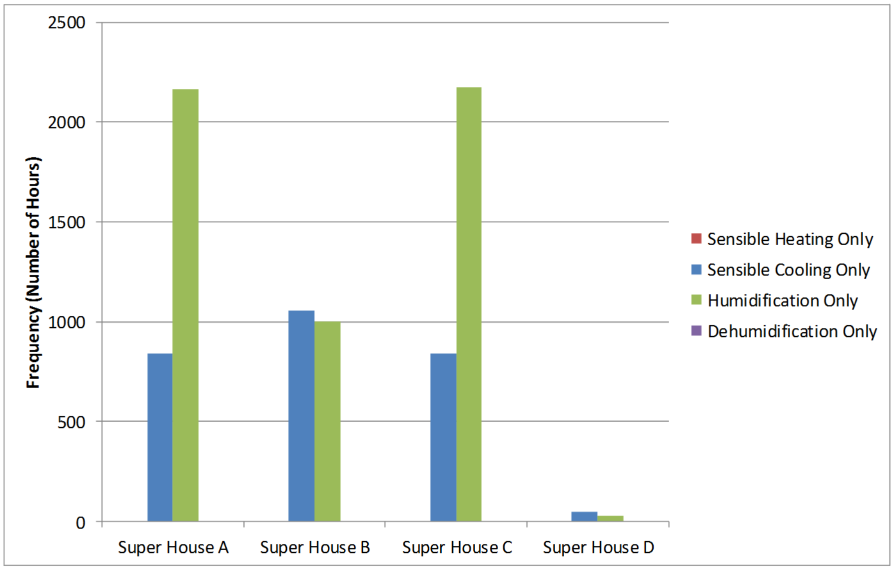


Figure C.3: Plot of load condition frequency, single load conditions

The next plot shows the four most likely load combinations within the house.

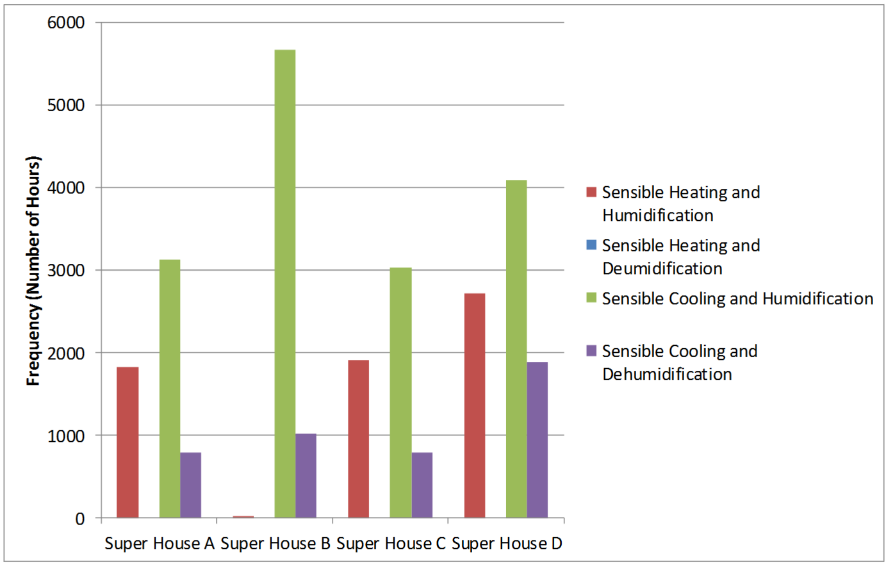


Figure C.4: Plot of load condition frequency, possible load combinations

C.3 All Houses

The final plots in this Appendix show the frequency of each load condition combination for all the houses. The first plot shows the frequency of the four load conditions when they occur on their own.

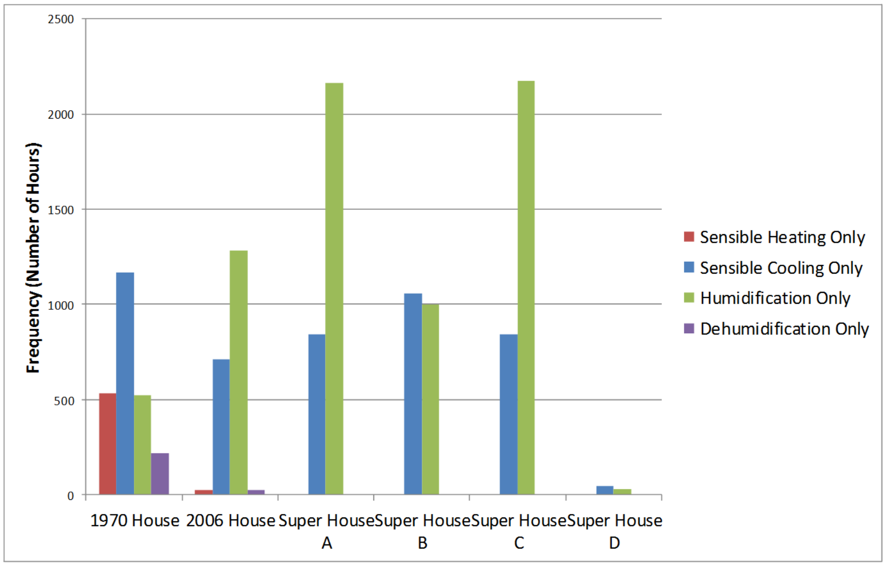


Figure C.5: Plot of load condition frequency, single load conditions

The next plot shows the total occurrences of each load condition, regardless of whether they occur on their own or in combination with another load condition.

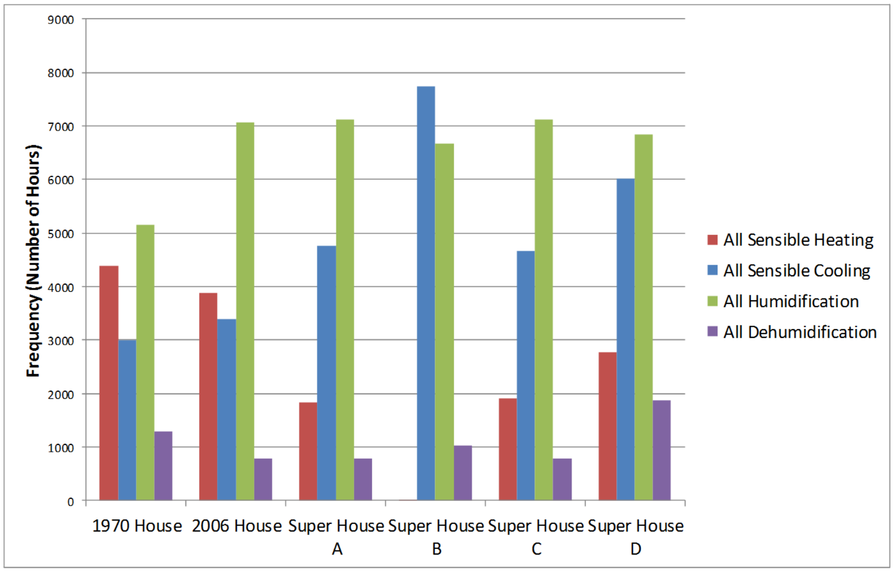


Figure C.6: Plot of load condition frequency, all load conditions

The final plot shows the four most likely combinations of load conditions for all six houses simulated.

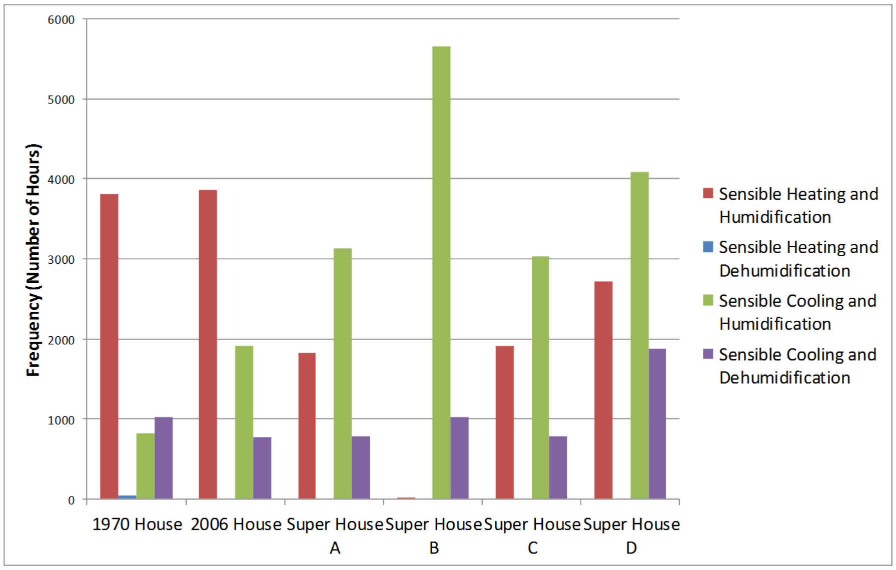


Figure C.7: Plot of load condition frequency, possible load conditions