THE DEVELOPMENT OF A MEASUREMENT METHODOLOGY TO COMPLETE A FULL ENERGY BALANCE FOR COMMERCIAL BUILDINGS

THE DEVELOPMENT OF A MEASUREMENT METHODOLOGY TO COMPLETE A FULL ENERGY BALANCE FOR COMMERCIAL BUILDINGS

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Abstract

There is a growing focus on the need for buildings to be energy efficient due to rising energy prices and the recognition of global warming. Over the past twenty years the sector that saw the least improvement from energy efficiency measures in Canada was commercial and institutional buildings. Though there are many contributing factors, they tend to stem from a lack of available information on building energy usage. In order to rectify this situation more information would be needed to better tune building energy efficiency measures to commercial buildings.

Most current research on building energy usage focuses on building consumption, building energy models, or direct measurements from residential buildings. There is little research on measuring a building energy balance of commercial buildings even though the commercial sector accounts for 20% of the overall building energy consumption in Canada. At present, all industry standards focus on the consumed energy in a building, generally natural gas and electricity consumption. Buildings consume energy to meet the demands for occupant comfort within the building and there are many different energy flows and parameters that affect the occupants' comfort within a building. Solar gain, conduction and infiltration are some of the energy flows that can negatively affect a building's temperature for occupants, reducing their comfort. In order to reduce the consumed natural gas and electricity, more information on the impact of these energy flows and parameters within a building is required.

A five step process was developed to guide the design of an in-situ system that is capable of measuring a complete energy balance of any commercial or institutional building. The focus in this research project is to create an accurate, cost effective sensor array that is a permanent fixture within a building. By utilising these semi-permanent sensors, the interactions between the different energy flows can be better understood. It will also generate more concrete evidence on energy flows to potentially improve building automation systems.

In addition to the process, a case study of the Hatch Centre on McMaster University's campus was completed, giving concrete examples that help to illustrate the procedure.

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To you, the reader, for taking the time out of your busy day to read this or at the least flip through and look at the pictures.

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Nomenclature

Variables

ΔQ	Balance of thermal energy through envelope of building [J]
$Q_{Generated}$	Thermal energy created by the HVAC system [J]
Q_{Stored}	Thermal energy stored in the building through thermal mass or thermal storage [J]
Q_{Latent}	Latent thermal energy stored in humid air [J]
$Q_{Conduction}$	Thermal energy transferred through the building envelope by conduction [J]
$Q_{Infiltration}$	Thermal energy transferred through building envelope by due to mass flow [J]
$Q_{Ventilation}$	Thermal energy transferred out of building from the HVAC system [J]
$Q_{SolarGain}$	Solar thermal energy transferred into building through transparent surfaces [J]
$Q_{Occupants}$	Thermal energy transferred to building through metabolic rates of building occupants [J]
$Q_{Electrical}$	Thermal energy transferred to building through waste heat from electrical components [J]
ΔE	Electrical energy balance of building [kWh]
$E_{Generated}$	Electrical energy generated from building energy generation systems [kWh]
$E_{Purchased}$	Electrical energy purchased from grid [kWh]
E_{Stored}	Electrical energy stored in building energy storage systems [kWh]
$E_{Consumed}$	Electrical energy consumed by building systems [kWh]
$\dot{m}$	Mass flow of a fluid [kg/s]

c_p	Specific heat capacity [J/kg K]
ΔT	Temperature difference between the outside air and the inside air [^oC]
ΔT_{LM}	Log mean temperature difference [^oC]
A	Area [m^2]
U	Heat transfer coefficient [W/m^2 K]
$\dot{q}$	Volumetric flow rate [m^3/s]
ρ	Density [kg/m^3]
P_T	Pressure due to stack effect [Pa]
P_U	Pressure due to wind speed [Pa]
Δp_I	Pressure from mechanical systems [Pa]
ρ_o	Outdoor air density [kg/m^3]
T_i	Indoor air temperature [^oC]
T_o	Outdoor air temperature [^oC]
H_{NPL}	Height of the neutral pressure level [m]
U_W	Local wind speed [m/s]
G_{Solar}	Average solar gain [W]
T	Fraction of incident radiation transmitted through window
S	Solar flux incident on window [W/m^2]

Acronyms

ASHRAE	American Society of Heating Refrigeration and Air-Conditioning Engineers
BAS	Building Automation System

CO_2	Carbon Dioxide
EVO	Efficiency Valuation Organization
HVAC	Heating, Ventilation, and Air Conditioning
IPMVP	International Performance Measurement and Verification Protocol
JHE	John Hodgins Engineering Building
LEED	Leadership in Energy and Environmental Design
NDIR	Non-Dispersive Infrared
NREL	National Renewable Energy Laboratory
NTC	Negative Temperature Coefficient
PTC	Positive Temperature Coefficient
RH	Relative Humidity
RTD	Resistance Temperature Device
VAV	Variable Air Volume

1.0 Introduction and Rationale

1.1 Introduction

Energy intensity in commercial buildings in Canada had slight decrease from 1.7 GJ/m^2 to 1.67 GJ/m^2 between 1990 and 2009 [1]. By comparison, the residential sector had a significantly larger decrease from 1.06 GJ/m^2 to 0.79 GJ/m^2 [1]. A key contributor is attributed to the amount of thermal and electrical wasted energy in the commercial building sector [1]. As commercial buildings consume roughly 14% of the energy in Canada, if the amount of wasted energy can be reduced, there can be significant benefits to national conservation efforts.

Without being able to precisely identify where the energy is being transferred throughout the building, it is hard to reduce the total energy consumption. For this reason, measurement and verification protocols have become an increasingly popular tool for determining improvements to building energy loads [2]. Active or real time measurement and verification can help alert building operators to instances of their building running at sub-optimal levels, such as when a valve or a damper is stuck. They can also help to improve the building automation system which is used to control the environment inside the building [2]. This research can also lead to the development of new energy efficiency measures by identifying energy flows that should be reduced in a building, as opposed to just consumption measures. These measures could be new technologies that are introduced or new conservation measures developed by a presiding entity that can improve current consumption levels.

Current measurement and verification protocols do not measure all of the energy flows throughout a building; they generally focus on energy that is consumed, generated and purchased [3][4]. This information is useful to building operators as it can give relative performance based historical data. The result is that by only measuring metered gas, electricity, and generated energy, specific energy flows within the building remain unknown. This poses a challenge in identifying if the building is operating optimally or when there are any issues that should be fixed and can allow for problems to compound over time, further increasing energy consumption. For example, if a building is uncomfortably hot during the cooling months there can be a host of reasons that an imbalance of heat energy is occurring. This could be caused by excess heat from external sources being introduced to the building or by a lack of heat being removed from the building. If there is no energy monitoring system in place to measure the buildings energy balance, this problem becomes increasingly difficult to rectify. This issue is a systematic one as there are no resources available for creating a system capable of completing a real time energy balance.

The Leadership in Energy & Environmental Design (LEED) program has a measurement and verification certification which focuses on energy that can be purchased, generated or consumed in a building [3]. Other industry design guides such as standards from the National Renewable Energy Laboratory (NREL) and the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) focus on the same types of energy flows[4][5]. A building owner inclined to create a robust energy monitoring system must design a new system for each building, increasing the costs of the design and the time spent. As building projects have strict schedules and budgets, a lengthy measurement design process limits their application.

Currently, the most popular way available to determine when the building is operating sub-optimally is by completing a building energy audit by a professional team, post occupancy. While these audits can give the insight required, an energy audit is a reactive solution that is completed intermittently. An energy audit that can reduce a building's energy is between \$2 to \$5 per square foot per year each time they are completed [6]. Other studies claim energy auditing leads to energy savings ranging from 5% to 50% with typical payback periods between 2-3 years [7]. Assuming these figures are consistent, and assuming the average building size is 1500 m^2, building energy audits can be assumed to cost between \$10,000 and \$25,000. As building issues may occur at any time, multiple audits are needed over the building lifetime to maintain designed performance. An improvement to energy auditing would be to monitor the energy and use benchmarks and building energy model predictions to immediately identify if energy flows were high and which energy flow was causing the increased energy use. A standard system of this type would offer more consistent savings in building energy and reduce the ongoing cost of operating a building. This is contingent on the system being developed in a cost effective manner with minimal measurement errors and required maintenance.

Measuring different types of energy flows that are not in standard measurement and verification standards has been occurring for decades. However, there is no resource to the author's knowledge that has compiled all of the information into best practices and given a process to be followed to allow for these non-standard energy flows to be measured. This is because in almost all cases a building energy model is considered to be sufficient to estimate what these energy flows will be in the future. While this is useful for making design decisions, it does not help to track the energy once the building has been completed. Factors such as weather and occupant behaviour can cause large changes in predicted and actual building energy consumption [8]. For example, the uncertainty of occupant behaviour can alter the actual measured energy use compared to the predicted energy use from an energy model by up to 150% [9]. These energy models also assume that all of the building systems are working perfectly throughout the duration. Due to the large discrepancy between the predicted energy use and the actual energy use, it is difficult to use energy models to make any concrete predictions on energy flows after the building has started operation. The result being you cannot create building benchmarks from the results of a building energy model, so the current strategy to create these benchmarks occurs from completing an energy audit.

The aim of this study is to identify opportunities to improve upon what is currently being done within building measurement and verification standards. This study will develop a step-by-step process to aid in the implementation of a robust building energy monitoring systems. This system will attempt to measure the complete building energy balance of a commercial building and will be a semi-permanent fixture in the building allowing for the data to be used in system diagnostics and the building automation systems. The process for designing the system will be robust enough that the system could be implemented into any new project; with a specific example building that is currently under development at McMaster University, the new Hatch Centre.

1.2 Background to the Study

The motivation for this study came from a proposed project for an engineering student centre at McMaster University called the Hatch Centre. The goals of the Hatch Centre were to create a sustainable building that would be a living lab of sustainability. The occupants of the building would be able to learn about sustainable features through observations throughout the building. The concept of a living lab of sustainability can be seen at Queen's University with the Live Building and at the National Renewable Energy Laboratory Research Support Facility in Golden, Colorado[10][11]. A living laboratory helps to transfer knowledge to the occupants through the building features and through the collection and dissemination of building information [12]. Bringing the building features and energy usage to the forefront of the occupants' attention they begin to understand more about the structure and can inquire on specific related information that interests them. The buildings at Queen's and in Golden, CO mentioned above also have comprehensive websites that describe the features and have an energy dashboard that occupants and other interested parties visualize and for research and teaching. The website and the kiosks are an essential part of the success of the living laboratory as these are primary ways to help disseminate information.

In order to include the energy information of the Hatch Centre in the interactive kiosks and the website, the energy must first be measured. As the building is an engineering student centre, there is the opportunity to also conduct building related research. To help increase the level of understanding and quality of research, it was proposed to create a system that is capable of measuring a complete building energy balance. In addition to this, the sensor array itself will be put on display to enhance the understanding of the complex interactions between thermal and electrical systems. The completion of this research project allows for many future research opportunities to occur at McMaster and also provides the potential to enhance the occupants' knowledge of building energy flows and energy monitoring.

There is significant opportunity for future research that can be completed based on the measurements taken using the sensor array. The most likely includes the integration of highly detailed measurements and predictive control systems. Initially it is expected that the building will be over monitored with the intent to determine the optimum sensors that are capable of actively controlling the energy system and identify novel energy drivers that can be used for predictive control purposes. Typically, occupancy and temperature are used to control the thermal environment but it is possible that other measurements can be more useful, such as weather, historical energy data, and external/internal measurements including zonal electrical load measurements, snow loading or wind speed directions as examples. Another application could be testing when building materials fail and determining different benchmarks for when this occurs. For example, how does conduction increase across the window if the seal has broken and the argon has leaked out and how does this failure impact the occupant comfort and building energy?

1.3 Scope of Work

This project will focus on creating a standard methodology for the selection and installation of sensors for a new commercial building. The design of this approach can use industry best practices as well as methodologies from prior research projects to shape the recommendations in this report. All energy flows will be modelled and their effect on a building energy balance will be discussed. Solutions for measuring each energy flow will be discussed and their merits will be judged relative to the alternative solutions. This will help lead to a selection of sensing principles that will be used throughout the building. Best practices for installation to help reduce systematic error will be discussed and supported with evidence from literature. An energy model will be completed on a building and the results will be utilised to help determine the location and number of sensors. The energy model will also help to determine the measurement ranges of energy for sensor selection and the values that should be used when completing the error analysis. These decisions include the amount of sensors that are required and their general locations in the building to reduce the systematic error of the system. A Monte Carlo Type-B error analysis will be completed for the array as a whole to ensure that the accuracy of the system was not "too high". Based on recommendations by the Hatch Centre project coordinator, this value was deemed to be 10% at 95% confidence.

2.0 Review of Literature

2.1 Historical Background

Building energy monitoring and verification has been evolving in North America since the 1960s and the first building energy simulations were performed on a mainframe computer in 1968[13]. One of the first international standards for measurement and verification, the International Performance Measurement and Verification Protocol (IPMVP) was created in 1995[13]. Since then, most building measurement protocols have focused on the total energy consumption in a building and how efficiency measures can be implemented to reduce consumption of electricity, thermal energy and water [14]. These protocols, while helping to improve energy efficiency in buildings, do not focus on the drivers of the building energy consumption, and instead only measure the aggregate energy consumption.

In the past twenty years there has been an increased focus on energy conservation and research has been completed in the green building sector to determine what factors drive energy consumption. The main driver for improving building energy consumption has generally been rising energy prices; in the 1970s with the oil crisis and in today's age with fluctuating energy prices in North America. Building energy efficiency is also driven by concerns about anthropomorphic climate change and consumer attitudes on social responsibility.

2.2 Review of State-of-the-Art for Measuring Building Energy

2.2.1 Previous Research on Measuring Building Energy

The research conducted on determining the energy balance of a building has been focused on improving the predictive qualities of energy models and estimating the energy drivers from total energy loads and other parameters.

Many different studies have been able to identify the thermal energy balance of a building and have attempted to complete methodologies to determine each parameter. In the residential sector, Lundin et al. [15] defined the heat balance as:

$$P_{tra} + P_{ven} + P_{dyn} - P_{heat} - P_{gain} = 0 \tag{1}$$

where P_{tra} is the heat transmission through the building envelope, P_{ven} the ventilation heat loss, P_{dyn} the dynamically stored heat, P_{heat} supplied heat to the heating system and P_{gain} is the heat gained from internal sources and solar radiation [15]. These values can be used define different generalized performance parameters of a building, including: the total heat loss coefficient, the effective heat capacity and the heat gain factor. In essence, they take typical measured values – temperature, air and liquid flow, area, and material properties – and use them to calculate the harder to measure values – solar heat gain, occupant gain, etc. Lundin et al. validated their model by creating a test cell 365mm x 400mm x 400mm. They installed three heat sources in the cell and used many thermocouples to determine the total thermal energy. By varying the ventilation and thermal energy entering the cell, by way of electrical heating coils, they were able to determine how each parameter affected the total energy balance of the cell and were able to determine equations for the above mentioned performance parameters. These values can be used to complete a building energy balance and to test the efficacy of them they were compared to a calibrated simulation. However, this is still not a measured energy balance but is more of an inferred energy balance.

Olofsson and Anderson completed a similar study where they took measured data from single-family residential buildings in a cold climate [16]. The measured building energy flows consisted of different temperatures, the energy used for space heating, and domestic hot water usage and the electricity usage of several domestic appliances. The space heating, domestic water and appliance load demand were all electrical based. Using these energy flows, as well as determining the mechanical ventilation, they were able to determine the building performance parameters as defined in the previous study to verify that the energy balance method proposed by Lundin et al. [15] could also be inferred in a residential setting.

Danov et. al created a new method for determining the same building performance parameters mentioned above [17]. In this study the focus was on the applicability to commercial buildings in a warm climate, as opposed to residential buildings in a cold climate. The fuel for heating, total electricity consumption, weather data was monitored and building occupancy was determined through a questionnaire filed by the building operator. They looked at determining the total heat loss coefficient by considering the solar gain and correcting the dynamic effects of the building with the energy associated with the thermal mass of the building. This was completed by determining the building's heat capacity then multiplying this value by the temperature difference between the outside air of the measured day and the outside air of the previous day. This was assumed to give an accurate value of the thermal energy associated with the thermal mass of the building. This is an improvement on the previous two studies, which did not take these effects into account. By using a regression model and correcting for solar gain this study was able to improve the predictive capabilities of the three performance factors.

These three studies show the importance that is being placed on better information about building energy usage. The challenge in the above mentioned studies is the limited measured data used to predict other factors of building energy usage and thus no attempt has been made at completing a dynamic measure of the thermal energy balance.

Rabi and Rialhe created an energy model that attempted to determine the effects of building occupants on the building energy, in an attempt to improve the predictable nature of models [18]. Their model looked at the behaviour of the building with consumption data as opposed to looking at material properties and schedules, such as what is seen in the DOE2 engine. By looking at the building behaviour through monthly utility data, they can use fewer inputs; however they must use a more complex statistical analysis.

They then applied their energy model to 50 different buildings in Paris and compared the total energy predicted in their model to the total energy reported on the utility meters. It was found that their model was significantly more predictive in over a third of the buildings, reducing the standard error by a factor of 0.9. The lack of predictability of their model in the other buildings may stem from the fact that their model was only calibrated for the complete end use through the energy bills. For a new build, this type of energy model is impossible to use. This study also shows a larger issue with energy modelling, where most models are overly focused on, and in some cases calibrated to, the metered data for utility bills. This is an issue because the building utility bills are the sum of the building energy flows. By being overly focused on the end result, the energy model can appear correct while the individual energy flows are wrong. This becomes an issue when looking at energy improvements as some energy conservation measures can be overlooked or overemphasised if the individual energy flows are not assessed correctly. By monitoring the smaller energy flows that make up the energy balance as well as the total utility bills it becomes much easier to see where energy improvements can be made. The energy model can then more accurately depict the energy flows, allowing a more accurate prediction for the conservation measures and their environmental and economic outcome.

It is known that the individual energy flows are important and that there are many confounding factors. For example, the impact of occupants on building energy has been studied [19] [9] and they all conclude that occupants have a large effect on the predictive qualities of building energy models, decreasing the predictive qualities of an energy model to 50% at times. These studies compare two energy models to each other, as opposed to an energy model to measured data. Without comparing the results of the energy model to real data the effectiveness of these models will always be uncertain. Energy modelling research will be improved as there will be primary data to which the results of the energy model can be compared.

Complimenting building usage research, there have been a number of different standards created that are currently utilised to aid in the design of an energy monitoring system. The current standards from large government or private agencies are all helpful when looking to monitor the electricity consumption of a building, however they are only capable of measuring consumption or generation, and the main drivers of thermal energy usage are not normally fully integrated into the building energy monitoring system. In the following section the different standards and how their best practices can affect this energy monitoring system will be discussed.

2.2.2 IPMVP Standard

The IPMVP was developed by the Efficiency Valuation Organization (EVO) to determine a consensus method relating to measuring and verifying water and energy efficiency savings [3]. The standard is continuously evolving and new protocols are introduced to meet the needs of current consumers of energy efficiency projects. The standard is now in its 7th edition. The IPMVP is one of the most accepted measurement and verification protocols as it is the basis of the LEED building certification program, the most popular building certification program in North America.

The goal of the current edition of the IMPVP is to assemble best practices from around the world to improve measurement and verification practices. It also provides a framework to make energy savings reports easier to understand for building operators and occupants. As such, this standard focuses more on verification and reporting than it does on measurement.

The standard has four options available: Option A: Measurement of the key parameters of a specific building technology, Option B: Measurement of all parameters of a specific building technology, Option C: Measurement of the entire facility at the facility level or Option D: Sub-facility level and using a calibrated simulation to estimate energy use. Only Option C will be considered in detail as it is the option that most closely resembles the goals of the project as it directly measures the energy of the entire facility.

When describing the metering that must be done in Option C, the standard advocates using the utility meters of the facility as well as using some extra facility specific monitoring for a more detailed measurement. These facility level meters include the total electrical consumption of the building and the total energy use of the HVAC system from either fossil fuels or electricity.

The information gained from this standard does not yield detailed results of the building sub-systems. This standard is also utilised when a building is about to undertake an energy efficiency measure to help determine what was the annual savings of that measure. However, by following this standard only the end result on the energy meter is determined, and what drove the reduction (or lack of reduction) of energy may be difficult to determine. This standard is helpful when determining what the energy savings were for the total building but it does not necessarily help to determine why that savings occurred without collaboration from an energy model.

2.2.3 NREL Standard

The next standard that will be discussed is the Procedure for Measuring and Reporting Commercial Building Energy Performance by the NREL. NREL is the primary laboratory for renewable energy and energy efficiency research and development in the United States. It is a government owned entity funded through the Department of Energy.

The purpose of the NREL standard is to establish a standard method for monitoring and reporting the energy performance of commercial buildings. The scope of the standard focuses on all forms of purchased energy; all forms of on-site energy conversion, such as cogeneration; and all types of on-site energy production. This standard, like the IPMVP, does not focus on the thermal loads in a building, which are the main driver of building energy consumption [4].

Unlike the IPMVP, this standard does have a focus on energy monitoring as well as reporting. The standard goes through many different metrics involved in measuring the consumption of energy. It identifies the common ways of generating electricity in a building including PV, wind and cogeneration; the consumption of the HVAC system and domestic hot water; the electrical loads within a building, including lighting, equipment and plug loads; and the purchased energy, including electricity and natural gas. These forms of energy directly impact the energy related cost in the building and effectively meet the goals of the standard, however this is not sufficient information to complete a full energy balance as there are other forms of energy within a building.

In order to make the standard more repeatable the standard describes the energy monitoring equipment. It goes through each measurement outlined in the previous section and gives a list of options. However, an objective method for sensor selection is not established which could lead to system issues as a sensor that is not well suited for the task may be chosen. This may cause increased capital or operational and maintenance costs through the life-cycle of the building. The lack of a methodology for choosing sensors is a common theme in the existing research practices and is a problem that must be solved as measurement and verification becomes more popular. While this standard is a resource for determining the consumed energy of a building, it must be advanced upon in order to meet the goals of the proposed energy monitoring system – to measure a full energy balance.

There is a significant lack of applicable standards for measuring at the scale of required completing a full energy balance. Some organizations that are known for their energy standards do not even have an adequate alternative. For example, there are ASHRAE 105-2014 and ISO 50001. ASHRAE 105-2014 focuses on the development of building energy performance standards and reporting greenhouse gases. Its primary focus is determining building energy use but again, does not focus on specific energy flows. ISO 50001 looks at creating a policy and targets for more efficient energy usage. It then has guidelines for measuring the energy improvements but this standard also does not focus on the energy flows that affect the utility bills.

The current state of the art for thermal energy monitoring is capable of measuring the $Q_{Generated}$, Q_{Latent}, $Q_{Ventilation}$ and Q_{Stored} as defined above. Research has been completed to infer the other terms in the thermal energy balance equation for both commercial and residential buildings but a thermal energy balance has yet to be completed. The fact that a significant amount of work has been done on inferring a complete energy balance demonstrates that developing a system capable of measuring a full energy balance fills a large gap in building energy research. A summary of this literature review can be observed in Table 1.

Table 1: Summary of Current State-of-the-Art for Building Energy Monitoring

Title	Researcher (Year)	Measured Energy
Development and validation of a method aimed at estimating building performance parameters	Lundin, Andersson and Ostin (2004)	Temperature, Flow Rate, Area, Electricity Consumption
Overall heat loss coefficient and domestic energy gain factors for single-family buildings	Olofsson and Andersson (2002)	Temperature, Flow Rate, Domestic Hot Water Demand, Heating Demand
Approaches to evaluate building energy performance from daily consumption data considering dynamic solar gain effects	Danov, Carbonell, Cipriano, Marti-Herrerro (2013)	Temperature, Heating Fuel, Domestic Hot Water Demand, Heating Demand, Weather Data
Energy signature models for commercial buildings: test with measured data and interpretation	Rabi and Rialhe (1992)	Electricity Consumption, Natural Gas Consumption
International performance measurement and verification protocol	Efficiency Valuation Organization (2012)	Total Electricity Consumption, Total Heating Fuel Consumption
Procedure for measuring and reporting commercial building energy performance	National Renewable Energy Laboratory (2005)	All energy consumed, purchased, stored or generated
ISO 50001	International Standards Organization (2011)	All energy consumed, purchased, stored or generated

2.3 Review of Energy Transfer throughout a Commercial Building

There are many different energy streams in a building that contribute to the total energy balance of a building. The thermal energy balance equation is [20]:

$$\Delta Q = \pm Q_{Generated} \pm Q_{Stored} \pm Q_{Latent} \pm Q_{Conduction} \pm Q_{Infiltration} \pm Q_{Ventilation} + Q_{SolarGain} + Q_{Occupants} + Q_{Electrical} \pm Q_{Negligbible} \text{ [W]} \quad (2)$$

Where the terms are, in order: the generated thermal energy from the HVAC system, any stored energy through thermal storage or thermal mass of the building structures, the latent energy in the air, thermal conduction through the building envelope, infiltration transfer through the envelope, solar gain from infrared radiation entering the building, the metabolic heat given off to the building from its occupants, the heat gain from the electrical use in the building, and the negligible energy flows such as the gain from domestic hot water. A diagram helping to illustrate this equation can be observed in Figure 1.

As can be observed, some of the energy flows pass through the control volume, affecting the energy balance of the building, while other flows are internal loads or sinks for the thermal energy. In general, for a building, there is a complete balance of energy and $\Delta Q = 0$. If there is an imbalance of energy in the building, and $\Delta Q > 0$, the temperature of the building will increase; if $\Delta Q < 0$, the temperature of the building will decrease. It is the job of the HVAC system to ensure that $\Delta Q \approx 0$ to keep the temperature of the building within the tolerable limits for the occupants. In the schematic below, the three components of the HVAC system are $Q_{Generated}$, $Q_{Ventilated}$, and $Q_{Stored,}$

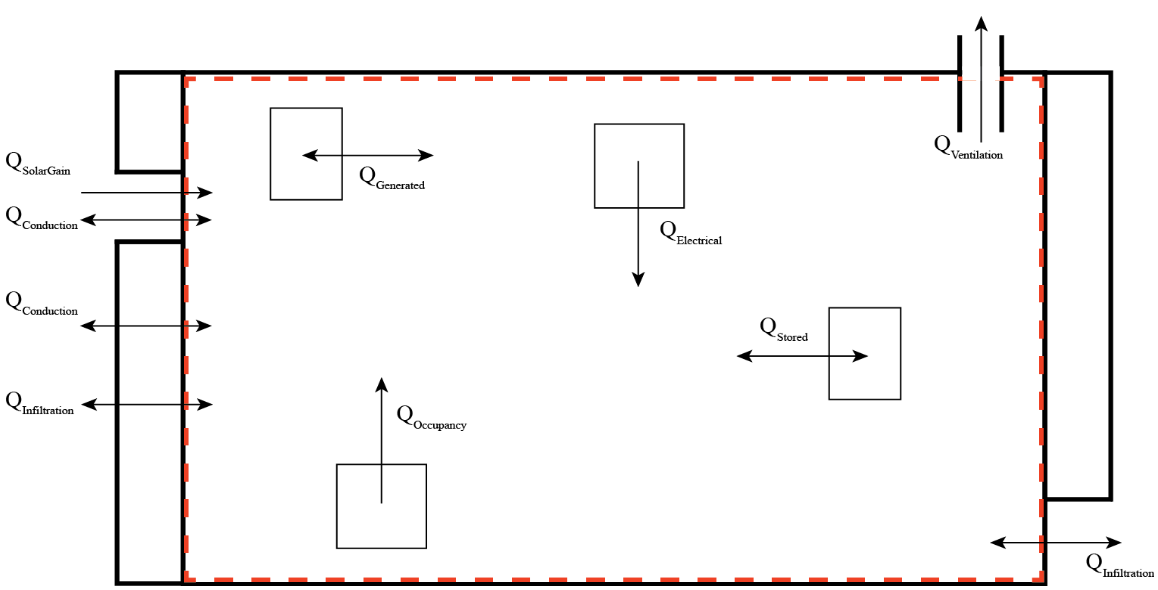

Figure 1: Schematic of the Control Volume for the Energy Transfer in a Commercial Building

The control volume for this system was chosen to be directly on the interior side of the building. This was done so that any thermal storage in the envelope of the building can be neglected. When energy transfer occurs on the exterior surface through convection, conduction and radiation, the energy may transfer into the building by way of conduction through the envelope. These energy flows can be captured through the conduction sensors. Energy which does not transfer into the building is of less importance as it does not have an impact on the energy balance inside the building, as such it does not impact the thermal comfort of the occupants. Any energy which impacts the thermal comfort must be counteracted by the building HVAC system, and as such has a cost associated with it. Any energy flow that does not impact the operational costs of the building was considered to be out of scope.

The electric energy balance equation is:

$$\Delta E_{Electrical} = + E_{Generated} + E_{Purchased} + E_{Stored} - E_{Consumed} \text{ [W]} \tag{3}$$

This is the electricity that is generated from any on-site generation, the energy that is purchased from the grid and any energy that is stored on-site; this must be equal to the amount of energy consumed in the building.

2.3.1 Thermal Energy Balance

Within the terms of the thermal energy balance there are many different types of energy flows that are important to quantify. In current measurement and verification protocols, the methods for tracking some of these energy flows are well known. However, other energy flows such as conduction, solar heat gain, occupancy, infiltration and gains from electrical equipment tend to not be directly measured. In general, electrical consumption, generation and storage as well as the loads generated by the HVAC system are typically the energy flows that standard design guides focus. These energy flows are chosen because they directly impact the energy consumption cost of the building. These flows also have a wide variety of sensing options that are designed to fit the needs of building energy monitoring. They include: advection heat transfer, heat transfer through heat exchangers, and electricity consumption. The energy flows which indirectly impact the energy consumption are usually indirectly measured as well. The result being there are limited sensing options for these energy flows and novel solutions must be adapted or developed to completely measure all parameters in the building energy flow. These energy flows include: conduction heat transfer, infiltration heat transfer, solar heat gain, and occupant heat gain.

Advection Heat Transfer

For the building HVAC system, in a commercial building, the main modes of energy transfer occur through the thermal energy transfer in liquids and the air in the ducts. The heat is transferred by advection through the governing equation:

$$Q_{Ventilation} = \dot{m}c_p\Delta T \text{ [W]} \tag{4}$$

Where $\dot{m}$ is the mass flow of the fluid, c_p is the heat capacity and ΔT is the temperature difference between the hotter temperature and the colder temperature.

Heat Exchanger Equation

There are also heat exchangers which transfer thermal energy from one medium to another. The general equation for heat transfer design is:

$$Q = UA\Delta T_{LM} \text{[W]} \tag{5}$$

Where U is the heat transfer coefficient, which is dependent on the design of the heat exchanger, A is the heat transfer area, also dependent on the specific design of the heat exchanger and T_{LM} is the log-mean temperature difference[21]. From these two equations it can be determined that the entire sensible heat load from the HVAC system is dependent on the temperature difference and sometimes the mass flow of the fluid. By measuring the mass flow and temperature of the fluid throughout the building, the values for $Q_{Generated,}$ Q_{Stored}, and $Q_{Ventilation}$ can be determined.

Conduction Heat Transfer

Thermal energy can also be transferred by way of conduction through the building envelope. For simple one-dimensional steady-state conduction the general equation is:

$$Q_{Conduction} = -kA\frac{\Delta T}{\Delta x} \text{ [W]} \tag{6}$$

However, the outside environment for a building is ever changing, thus conduction is usually a transient problem. When thermal mass is added into the equation for conduction it becomes even more complicated. Determining the conduction losses over a set time period can compound errors if thermal mass was incorrectly determined. Further, if the thermal envelope of the building was installed incorrectly, the R-value of the materials will be different from the manufacturer's specifications. For these reasons, it is more accurate to directly measure the conduction through the walls and windows, as opposed to the temperature difference of the surface and find an analytical solution. This is typically done with a heat flux transducer and will be discussed further on.

Infiltration Heat Transfer

Air mass transfer through the building envelope is another method of thermal energy transfer in buildings and account for anywhere from 20% to 50% of the building energy heat loads. This type of energy transfer is called infiltration when the outside air is entering the building and exfiltration when the inside air is escaping to the outside environment. Even though buildings can undergo both infiltration and exfiltration at any time, both processes will be referred to as infiltration for the remainder of this report. The governing equation for infiltration is [22]:

$$Q_{Infiltration} = \dot{q}\rho c_p \Delta T \text{ [W]} \tag{7}$$

Where $\dot{q}$ is the flow of air in m^3/s, ΔT is the difference between the inside air temperature and outside air temperature, ρ is the density of air and c_p is the specific heat of air. The air flow measurement for infiltration is dependent on the pressure difference between the indoors and outdoors, which is dependent on many factors. The different factors that affect pressure are the stack pressure, wind pressure and the general leakiness of the building. The total effect of all of these parameters can be defined by the equation [22]:

$$\Delta p = s^2 C_p P_u + H_{NPL} P_T + \Delta p_I \text{ [kPa]} \tag{8}$$

Where P_T is the pressure change due to the stack effect, P_u is the pressure change due to the wind pressure and Δp_I is the pressure that balances the airflow due to other effects such as the mechanical systems. The stack effect occurs due to the hydrostatic pressure caused by the mass of air inside or directly outside the building. This pressure difference can be measured directly through the use of multiple pressure sensors on the interior and exterior of the building.

The pressure difference is related to the infiltration rate through how airtight the building is. To adequately measure the rate of change in the building a tracer gas test can be performed. There are many different types of tracer gas tests that will be discussed later in this report. In general, the tracer gas test consists of a source of a specific gas and a receiver that is sensitive to the tracer gas. The receiver measures the concentration of the gas in the room and as the concentration changes over time the rate of mass flow through the building envelope can be determined. The results from the test can then be correlated to the pressure difference from the above equations and the thermal energy transfer from infiltration can be estimated.

The infiltration value could also be determined through a blower door test. In a blower door test a large fan is temporarily installed at the main entrance of the building. The building is depressurized through the fan and the ventilation systems are sealed. A value of the infiltration rate can then be determined based on the pressure difference and the flow rate of air leaving the building. For a large commercial building, it is difficult to adequately depressurize the entire building through a blower door test.

Solar Heat Gain

The solar heat gain in the building is split between two distinct parts, the direct sunlight and the diffuse sunlight that enters through the windows. The total solar gain in a building can be determined through the equation:

$$Q_{solar} = A_w \times T \times S \text{ [W]} \tag{12}$$

Where Q_{solar} is the average solar gain in watts; A_w is the area of the opening in m^2; T is the fraction of incident radiation transmitted to the interior; and S is the solar flux on the surface in W/m^2 and is measured by the pyranometer [23]. The fact that the solar energy can be split into diffuse and direct sunlight is an important factor to consider as well. Depending on the amount of shading on the building, the total amount of solar energy entering the building can be different, even though the orientation of the surface is similar. This effect will be discussed in more depth in section 4.3.

The amount of solar flux through a surface is dependent on the orientation of the surface and the angle of the sun in the sky. Because of this, the amount of solar flux on a surface will vary both throughout the day and throughout the year. The system used to measure the solar heat gain must be able to account for all possible variations in solar energy, including the percentage of surface area of the building that is shaded.

Some of the solar energy is absorbed by the opaque surfaces of the building. Any amount of this energy that may enter the building will be determined through conduction measurements. Some of this energy will be dissipated through convection and

Occupant Heat Gain

Building occupants are a large source of thermal energy in a given space due to the metabolic rate of each person within the zone. The governing equation for the energy added by the occupants is given by:

$$Q_{Occupant} = \sum_{r=i}^{n} q_i \text{ [W]} \tag{13}$$

Where n is the number of people in the building and q_i is the individual metabolic rate of each person. In order to measure the effect of building occupants on the energy balance, the number of people in the building must be tracked. There must also be a way to account for the individual metabolic rates. This amount can be measured directly or an average can be used to estimate the total thermal energy. By estimating the individual metabolic rate, the total uncertainty in the measurement increase, but the total cost of the measurement decreases. Research shows that metabolic rate is affected by age, weight, and activity level. Assuming all the occupants are at the same activity level, the deviation of individual metabolic rates from the mean is 30% [9].

Electric Load Heat Gain

Finally, the electrical energy loads also affect the thermal energy loads in the building. The thermal energy is dependent on the electrical energy consumed by each individual piece of electrical equipment. As a result, while the thermal energy from electrical consumption can be measured using an aggregate meter. By sub-metering the different areas or types of equipment, a better estimate of the thermal energy from electrical consumption can be determined.

2.4 Review of Instrumentation

There is variety of sensors that are required to complete the total building energy balance. A summary of the parameters that must be measured and the different sensors that are capable of measuring these values can be seen below in Table 2.

Table 2: Required Parameters to Measure a Full Energy Balance and the Corresponding Sensors

Parameter	Sensing Solutions
Liquid Temperature	Thermistor, RTD, Thermocouple
Air Temperature	Thermistor, RTD, Thermocouple, Infrared
Liquid Flow	Coriolis, Differential Head, Turbine, Electromagnetic, Vortex Shedding, Ultrasonic
Air Flow	Pitot Tube, Hot Wire Anemometer, Thermal Dispersion
Thermal Conduction	Temperature Difference, Schmidt-Boetler Sensor, Thermopile
CO_2	Chemical Reaction, Non-Dispersive Infrared
Electric Load	Non-Socket Electronic, Feed Through Meter
Solar Gain	Silicon PV, Thermoelectric
Shading	Image Processing, Photodetector Array, Software
Wind Velocity	Vane Anemometer, Ultrasonic
Infiltration	Blower Door Test, Tracer Gas Test
Occupancy	Thermal Imaging, Computer Imaging, Optical Turnstile

Temperature Sensors

For the temperature sensing devices the options include thermistors, thermocouples, RTDs and infrared measurements. Determining temperature from infrared measurements involves the use of the equation:

$$q = \varepsilon\sigma T^4 A \tag{14}$$

Where ε is the emissivity of the material, σ is the Stefan-Boltzmann constant T is the temperature of the surface and A is the area of the surface that the sensor is measuring. At temperatures typically seen in a building the wavelength of the radiation is in the infrared spectrum. The sensor measures a value for q by measuring the infrared radiation off an object. By rearranging the above equation, a temperature can be inferred. However, the emissivity of a surface is generally uncertain. The area that the sensor is measuring must be known. These inherent qualities of infrared sensors increases the uncertainty associated with the measurement. Infrared sensors are generally expensive. It is difficult to utilize them to measure the inside of ducts and impossible to measure the inside of pipes with fluid flowing. This increases the installation costs and reduces the reliability [24].

Thermocouples are an inexpensive option for measuring temperature throughout a building with small upfront costs due to the simplicity of the installation. However, due to the nature of thermocouples the long term reliability of the option is tenuous. Thermocouples drift at a rate of 3% per year increasing the operation and maintenance costs associated with the sensor. Thermocouples also create low voltages and as a result they are susceptible to interference from electromagnetic radiation, known as noise, reducing the accuracy of the reading. Thermocouples can be installed just about anywhere in a building. They are good for high temperature applications however most building temperatures do not exceed 100^{o}C making the high temperature applications an unnecessary feature. Due to the increased maintenance over the years due to constant need for recalibration, thermocouples may not the best option to measure temperature in a building [25][26].

The next two options to choose from are positive temperature coefficient (PTC) sensors and negative temperature coefficient (NTC) sensors. Both sensor types work on the same principle, they both utilize a resistor whose electrical resistance value is dependent on the temperature of its surrounding environment. They differ as PTCs increase resistance with increased temperature, while NTCs decrease resistance with increased temperature. The most common type of PTC sensor is known as a resistance temperature detector (RTD). RTDs can be installed in the variety of environments that will be found throughout a building, giving accurate measurements in temperatures well over 100^{o}C [26]. RTDs are a stable sensor and have good long term stability. Their relationship between temperature and resistance is linear, making a higher accuracy than the other sensing principles. However, most RTDs are made of expensive materials such as platinum, highly increasing their per-unit cost.

By comparison, NTC devices are made of metal oxides whose resistances decrease as temperatures increases. The most common type of NTC device is called a thermistor. As thermistors are made from metal oxides the per-unit cost much lower when compared to RTDs, but higher when compared to thermistors. The relationship between temperature and resistance is non-linear at high temperatures, which reduces the accuracy and the long-term stability when compared to RTDs. This also limits the temperature range of the measurements to around 100^{o}C [25][26].

Liquid Flow Sensors

Some buildings use liquids as one of the energy transfer mediums of the HVAC system. This can commonly be seen with a hot-water radiant panel system where the hot water is supplied by a dedicated boiler system. Usually the heat transfer medium is water, but in some cases, the water is mixed with glycol to lower the freezing point to reach cooler temperatures of the water.

There are a number of options for measuring the flow of fluid throughout a building. There are Coriolis, differential head, turbine, electromagnetic, vortex shedding and ultrasonic flow meters available.

Coriolis flow meters are high performing when comparing accuracy, robustness and reliability [27]. However they are expensive; at around $3500 per unit before installation [28]. As such, their cost is too restrictive for the expected number of measurements for in a building and should be disregarded for that purpose.

Differential head flow meters include Venturi meters and orifice plates. They work on the principle of varying the cross-sectional area of the pipe which creates a pressure drop in the system. By measuring the pressure difference before and after the orifice, the flow rate of the water can be obtained. These sensors are both accurate and reliable over the duration of their life. Venturi meters, however, are not cost effective due to the complex machining required to create them. They must be located inside the pipe, so if the device is to be removed for any reason, flow to that area of the building must be shut down. While the devices themselves are stable, the major reading comes from a pressure transducer. These devices tend to drift by from 0.75 PSI to 3.0 PSI per year and thus need to be recalibrated annually to maintain the accuracy of the system, increasing the maintenance costs and general upkeep [29]. The differential head flow meters also add a pressure drop to the system with each flow meter and many flow meters can increase the building costs due to the need for larger pumps [30].

Turbine flow meters are an in-line flow meter that uses the dynamic energy of the fluid it is measuring to rotate a small turbine. The rotational speed of the turbine rotor is proportional to the speed of the fluid. The speed of the turbine is generally measured magnetically, with a piece of embedded magnetic material at least one of the turbine blades. A sensor, located outside the pipe, creates a pulse whenever a magnetic blade passes by it. A processor calculates the flow based on the derived pulse signal [31]. While turbine flow meters are accurate and cost effective, they have moving parts, which makes them less reliable than options that are static. They also have a significant pressure drop, much like differential head flow meters, that makes them unsatisfactory for building fluid flow measurement due to possibilities of increased pumping costs.

Electromagnetic flow meters work through the principles of magnetic induction. Magnetic coils placed around or near the pipe create a controlled magnetic field. A voltage gauge inside the pipe measures the intensity of the magnetic field. As a conductive fluid passes through the pipe it perturbs the magnetic field which varies the voltage measured. From this, the flow rate can be calculated [32]. Electromagnetic flow meters have little maintenance costs due to having no moving parts. They also add little pressure drop to the system by having most of the sensing equipment on the outside of the pipe. This also makes installing and replacing these sensors much easier. Electromagnetic sensors are fairly expensive though, and there is a minimum requirement for electrical conductivity for the sensor to work properly. Therefore, if the conductivity of the measured fluid is too low, the uncertainty of the system can be increased [33].

The next type of flow measurement is vortex shedding. A vortex shedding meter is an in-line type flow meter. A vortex shedding meter uses a small cylinder inside a pipe to act as a bluff body. As the fluid passes the body a vortex is created. The device measures the frequency of the vortices as they are created and this can be related back to flow velocity. As there are no moving parts, the reliability is comparably higher than devices that have moving parts. The pressure drop is smaller compared to other in-line flow meters due to the small bluff body added to the system. As long as the flow is larger than 0.3048 ft/s everywhere in the building the vortex shedding flow meter is adequate to use. Vortex shedding flow meters have fairly expensive upfront costs, around $1000 per unit, however they require little maintenance and upkeep, costing much less over their lifetime than the other sensors mentioned [34].

The last type of liquid flow sensor that will be discussed is an ultrasonic flow meter. There are two types of these sensors, a Doppler flow meter and a transit time flow meter. In both types of sensors, an ultrasonic flow meter sends an ultrasonic signal downstream from a transmitter to a receiver. For Doppler flow meters, there is only one signal sent. For a transit time flow meter, the signal is sent back upstream. For both sensors, the transit time is dependent on the flow of the liquid and a linear relationship can be derived between the two. Ultrasonic flow meters are installed on the outside of the pipes and do not obstruct the flow. This means there is no associated pressure drop with the sensor and no possibility of needing to increase the pump size due to a number of sensors in the building. They also have no moving parts which increases the reliability of the sensor in comparison to other sensors. Ultrasonic flow meters should be limited to fluids which can pass ultrasonic signals; all fluids in a building that will be measured are able to be used. Transit time sensors are generally more expensive but are much more accurate due to increased linearity [35].

Air Flow Sensors

There are a number of ways to measure the air flow throughout the HVAC system. The most effective methods are Pitot tubes, hot wire anemometers and thermal dispersion methods.

A Pitot tube measures the stagnation pressure and the static pressure at the inlet to determine the local air velocity. This is done through the equation:

$$u = \sqrt{\frac{2(p_t - p_s)}{\rho}} \tag{15}$$

Where p_t is the stagnation pressure and p_s is the static pressure. The pressure difference is measured by an electric transducer which determines the pressure difference, and the velocity of the flow can be inferred. Pitot tubes do not have any moving parts and do not use a pressure transducer; as such their reliability and robustness are high. They are accurate devices for measuring the local flow however in larger ducts, the local flow at a given point may not be indicative of the bulk flow rate throughout the duct due to the velocity profile of the air flow as seen in Figure 2 [36].

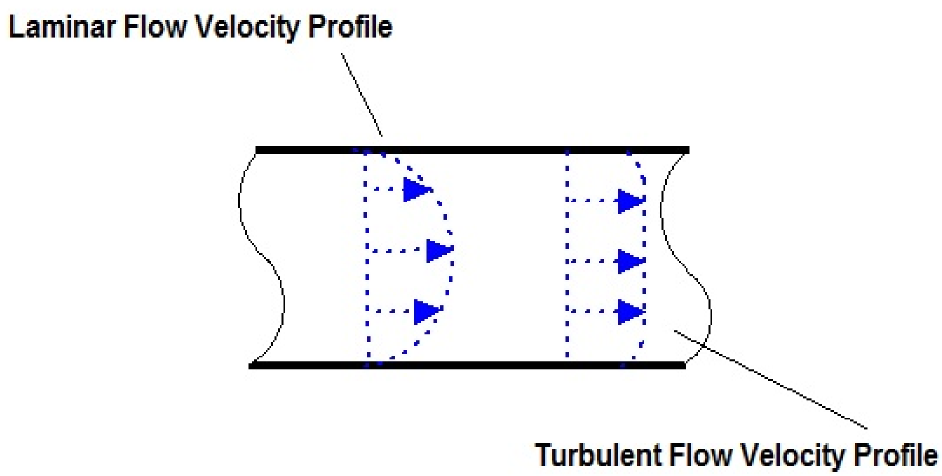

Figure 2: 2-Dimensional Velocity Profile of Air in a Duct

Because of this, there must be an array of sensors inside the duct to better estimate the flow rate. This increases the initial costs of the Pitot tube array. While Pitot tube array devices have been developed, these have more uncertainty than other options as these devices are still in their infancy.

A hot wire anemometer has the same issues, even though it is run on different principles. A wire is placed in the flow stream perpendicular to the flow and a current is run through the wire to keep it at a constant temperature. As the air moves over the wire it decreases the temperature and the current must be increased in order to keep the temperature constant. The amount of current drawn can be used to estimate velocity. These devices are relatively accurate. They also have no moving parts which makes them reliable. However, like Pitot tubes, they only measure the local air velocity and the technology currently is not able to make multiple cross-sectional measurements [37].

The next option is a thermal dispersion sensor. It works on a similar principle to a hot-wire anemometer, however, a thermal dispersion device has two resistive elements, one of which is heated, the other is not. As the flow rate increases, the temperature difference between the two temperature sensors decreases in a linear fashion. The temperature difference between the two resistors is measured and a velocity can be determined. Due to the linear relationship between temperature difference and flow rate, the device has a high accuracy. There are, again, no moving parts which gives a high reliability to the sensor. In addition to these features, there are devices that measure the air flow in multiple locations at the same height. For larger ducts, many different devices can be installed at different heights to get a better estimate of the bulk flow. The devices have also been designed to calculate the mass flow of the air, in addition to the volumetric flow, as the temperature is also being directly measured at the same location. These devices combine the temperature and flow rates and automatically correct for changes in thermal properties. This helps to reduce the amount of sensing points and shifts computational power to the sensor, which helps to reduce the total cost of the system [38].

CO_2 Concentration Sensors

While CO_2 is not an energy flow, it is still useful to measure. It is a link to building occupancy, which offers an inexpensive alternative to using an occupancy tracking system. It can also be used as a benchmark for a BAS, where if CO_2 is outside of the expected tolerance it can signal issues with the HVAC system. It is also a main parameter of occupant comfort, which is not related to building energy but is important when dealing with commercial buildings as there is a negative correlation between high CO_2 levels and productivity. This is important to keep in mind for the energy monitoring system as an energy savings measure may decrease the operational cost of the building, but if occupant comfort is too low it may also decrease the profits the building generates as well.

To effectively measure the CO_2 concentration in the air the only effective option is a non-dispersive infrared (NDIR) sensor. The only alternative is with a chemical sensor. This is not ideal as chemical sensors work with an irreversible chemical reaction to determine the concentration of the gas in the zone. This reduces their longevity and increases the lifetime costs of the sensor array [39].

NDIR sensors take advantage of the interaction between light and gases. The key components to these sensors are an IR lamp, a sample chamber, a wavelength filter and an IR detector.

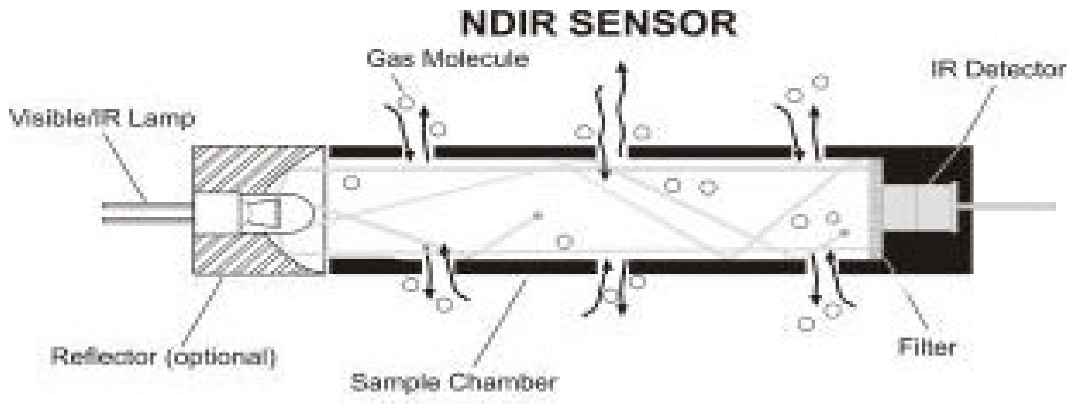

Figure 3: Schematic of an NDIR CO_2 Sensor

The IR light is directed through the chamber towards the IR detector. The gas diffuses into the sample chamber and attenuates the amount of IR light that reaches the detector. The detector has an optical filter to ensure that only the wavelengths the selected gas can absorb are detected. For greater efficiency a reflector can surround the IR lamp, although this is optional. Use of a reflector can increase available light intensity by two to five times, reducing the power requirements of the sensor. The intensity of the IR light that is detected is inversely related to the concentration of the gas in the chamber based on Beer's Law:

$$I = I_0 e^{kP} \tag{16}$$

With I_0 the light intensity for an empty chamber, k a system dependent constant and P the concentration of gas to be measured. Rearranging for concentration gives the equation [40]:

$$P = \frac{ln(I/I_0)}{k} \tag{17}$$

<u>Relative Humidity Sensors</u>

Relative humidity is another parameter that is not an energy flow but is recommended to be measured. The same arguments as above hold true here, where RH can be a benchmark for the health of the HVAC system or the thermal envelope. It can also be a medium for energy storage with the latent heat in the air. Finally it is also important for occupant comfort.

The two options to measure relative humidity are a capacitive type humidity sensor or a resistive type humidity sensor. Capacitive humidity sensors work by utilizing a material whose capacitance changes as it absorbs water on its surface. The material is placed between two electrodes to form a capacitor. As the capacitor comes into contact with the moisture in the air the capacitance of the device increases. Capacitive type sensors are linear and can measure from 0% to 100% RH improving their accuracy relative to resistive type sensors. However, in order to measure humidity, they require a complex circuit and need regular calibration this increases their lifetime costs [41].

Resistive humidity sensors use a material whose resistive properties change when it comes into in contact with moisture in the air. They use a conductive metal deposited on a substrate to act as an electrode. A conductive polymer is applied to the electrode. When the polymer comes into contact with the moisture in the air, the water molecules change the conductivity of the material. Resistive type sensors cannot measure below 5% RH, which in a building is irrelevant as the relative humidity should be between 40% and 60% [42]. Resistive type sensors are generally more stable in their operating range as they are more resistant to corrosion. Resistive humidity sensors have a lower lifetime cost than their capacitive counterparts [41].

Thermal Conduction Sensors

There are few ways to measure thermal conduction through walls and windows. It can either be done directly through the use of thermopile type sensors or Schmidt-Boelter type sensors or indirectly from the use of temperature difference and the heat transfer properties of the wall.

By measuring the surface temperature of the inner and outer wall of an area and assuming that the conduction is at steady state, the thermal flux can be described through the equation:

$$\frac{\Delta Q}{\Delta t} = \frac{A\left(-\Delta T\right)}{\frac{\Delta x_1}{k_1} + \frac{\Delta x_2}{k_2} + \frac{\Delta x_3}{k_3} + \cdots}. \qquad (18)$$

Due to the constantly changing exterior boundary condition, the system is generally in a transient condition as opposed to the steady state solution. This will inherently decrease the accuracy of the reading and the errors will compound over the lifetime of the sensors, quickly making the conduction estimate useless.

Schmidt-Boelter sensors work by absorbing heat flux at the sensor surface and then transferring the thermal energy to an integrated heat sink at a different temperature from the sensor surface. The temperature difference between the paths of the heat flow to the sink is a function of the net absorbed heat flux. An EMF is generated by the multi-junction thermopiles responding to the temperature difference. This EMF is measured and related to the thermal conduction. These types of sensors are robust and reliable; however they are expensive as they require a way to remove the heat from the reference junction. Their application is generally to measure fire resistance of materials which implies that they are far too robust for this application [43]

The thermopile type heat flux sensor works similarly to a thermocouple in that there are two dissimilar metals combined at a hot and cold junction. In between the two junctions is a thin film. As the thermal energy passes through the thermocouple junction and through the film it creates a small voltage due to the Seebeck effect. This voltage can be amplified by combining many of these thermocouple junctions together in layers. Due to the nature of thermopiles, this type of sensor is self-powered. Thermocouples tend to drift so the reliability is not ideal for constant measurement over a lengthy period of time [44].

Solar Gain

Devices that measure solar energy are called pyranometers. There are two types of pyranometers, a thermoelectric type and a silicon photovoltaic type.

A thermoelectric type pyranometer has large number of thermocouples layered then mounted on a black carbon disc, much like a heat flux transducer mentioned above. The thermocouples measure the temperature of the device, which is dependent on the solar energy being measured. In order to protect the device, there are one or two layers of glass domes made from either polished optical glass or acrylic plastic. This covers the thermopile, eliminating air movement and ensuring dirt does not enter the device. A replaceable desiccant helps to absorb any moisture. The output of these is in the mV range so an amplifier is necessary to ensure the device is not susceptible to noise. In order to measure total solar radiation it is acceptable to use one pyranometer. Thermoelectric pyranometers are accurate and reliable, but have significant initial costs associated with them. They have a wider range of wavelengths they are able to measure, compared to the silicon type [45].

A silicon photovoltaic pyranometer utilizes a small silicon photo diode that works on the same principles as a solar cell. They typically measure from 400-1100 nm getting most of the solar spectrum, with about 5% accuracy. It can measure intensities from 0 to 1280 W/m^2 allowing it to work anywhere in Canada. They are generally small and easy to move. They can come with a variety of mounting brackets and attachments dependent on the situation they will be used in.[46] Typically, they are less expensive than thermopile type pyranometers with a smaller range of wavelengths. This is not as important for measuring the energy that enters the building as glass attenuates 100% of the infrared radiation from the sun.

Wind Speed

From Section 2.3 it was noted that for infiltration measurements the wind was only required to be measured in the x-y axis and that the angle of the wind in the z-direction was irrelevant. For this reason, only the applicability of two-axis wind sensors will be analyzed. The two main options for measuring 2-axis wind speed and direction are a vane anemometer and an ultrasonic anemometer.

Vane anemometers are split into two types, where wind speed and velocity are combined in the device and where they have been split into two separate devices. In either device, wind speed is measured by harnessing the mechanical energy of the wind through either a cup anemometer or a propeller style. The wind direction is measured by a fin perpendicular to the x-y plane that moves with wind direction. These types of devices are cost effective but the largest downside is their abundance of moving parts. This reduces the reliability of the device. The devices are cost effective but are also less accurate than the ultrasonic devices [47].

Ultrasonic anemometers use ultrasonic sound waves to measure the wind velocity. Each device has 4 ultrasonic converters that are orthogonal to each other. The converters act as both transmitters and receivers. The converters send ultrasonic signals to each other and the device measures the transit time. The transit time is then dependent on the speed and direction of the wind. These devices have no moving parts and are ideal for long term weather measurements. They are more accurate than the vane type anemometers. Even though they cost more upfront, they have a smaller lifetime cost as well [48].

Occupancy Gains

There two ways to measure occupancy gain in buildings, direct measurement of occupant heat gain or estimating the occupant heat gain while directly measuring the number of occupants. Thermal imaging is currently the best method for tracking individual heat signatures from building occupants. Alternatively, the number of occupants in the building can be measured and an average metabolic rate can be estimated for all occupants. There are many different methods for tracking occupants in a building and they will be discussed below.

Computer vision systems use a camera to send a signal to a DAQ device, such as a computer. The signal is sent over the system internet to image processing software which then determines the number of people in the building. The systems have significant up-front capital costs are computationally expensive. The accuracy is highly dependent on the quality of the installed equipment and software. The system is highly susceptible to environmental effects, as background information must be digitally removed before the number of people can be calculated. This means that the system is susceptible to changes in light level and shadows. The cameras must also be able to see all of the floor area to accurately measure the number of people in the building, increasing the total lifetime costs, as there are more devices that will eventually fail and need to be replaced over the lifetime of the system. [49] Privacy concerns may be an issue with some occupants and can result in pushback with these sensors.

Thermal imaging systems use an array of infrared sensors to detect the heat sources of the occupants in the building, instead of using a camera to determine each individual in the building. These systems are typically mounted overhead to reduce the interference of other inanimate objects in the building. Occupant thermal imaging sensors detect the emitted heat from people, allowing for them to be implemented in all levels of lighting and do not require image processing algorithms to remove background objects, such as in the vision systems. This leads to a more stable and accurate measure of occupancy. This can also give more accurate readings of the energy given off by people as it is directly measuring their heat signature. It helps to alleviate privacy concerns as only the infrared image of the occupant is known and cannot be used to identify a person. The lifetime is usually 25 years and the accuracy is around 98%. These systems are usually expensive, usually starting around $1300. However, this type of measurement in a building is difficult as it requires a clear view path to the floor and is still computationally expensive [49].

The final option that will be discussed is an optical turnstile. The system was successfully tested by a McMaster Capstone group [50]. The system consists of a webcam placed above it at the entrance point and two reflective strips beneath it. The webcam's light filter has been replaced with a visible light filter, only allowing IR light into the aperture. The webcam signal is sent to a computer with an installed program that can determine when the reflective strips have broken. As there are two strips the direction of travel can also be determined and the people entering and leaving the building can be directly tracked. The accuracy for this system was tested to be about 95%. The installed cost is around $50-$100 for each unit. The number of devices needed to keep track of the building occupancy is minimal, as they are only required near the entrances and exits. This reduces the total system cost. The devices are well suited to their environment, and replacing broken sensors is easy, as they are located above each door [50].

Figure 4: Representation of Signal Sent to Image Processing Software from Optical Turnstile Sensors with Arrows to Denote Movement

Infiltration

There are two available options to determine the infiltration rate through the envelope in a commercial building, a tracer gas test or a blower door test. Both are able to determine the leakiness of a building, however, both require the space they are testing to be unoccupied, this means that the leakiness is generally determined during the commissioning phase of the building and sporadically throughout the building lifetime and thus infiltration is not directly measured. As discussed in Section 2.3, infiltration is dependent on wind speed and pressure difference. Both of these parameters should be measured at the same time of the initial test during the commissioning phase. A correlation may be found that can relate either one or both of the parameters to infiltration, allowing for this energy flow to be estimated throughout the building life time.

A blower door test works by temporarily installing a large fan on the main entrance to the building. The fan blows the air from inside the building to the outside environment causing a negative pressure. An expert can then go around to the exterior envelope and with a smoke pen can determine where the locations of infiltration can occur. To determine the infiltration coefficient, the pressure difference between the inside and atmospheric is measured. By measuring the pressure difference and also measuring the flow rate of the fan, the infiltration rate can be determined through a mass balance. This gives a baseline measurement for the building leakiness and the immediate infiltration rate can be determined through the correlations discussed earlier in the report. The effectiveness of the blower door test is limited by the volume of the building, as the more air inside the building the harder it will be for the fan to remove the air. If a building is larger than a residential house a blower door test becomes increasingly difficult to complete, even though it is a cost effective method to determine the base infiltration rate.

In lieu of a blower door test, a tracer gas test can be done to determine the infiltration rate. A tracer gas test uses a tank of a specific gas for a source and has a receiver that is able to measure the concentration of the gas in the zone. The leakiness of the building is correlated to the measured concentration. The correlation differs depending on the type of test that is being utilized. A tracer gas test has the added benefit of determining the infiltration rate under specific weather conditions. It can also help to determine the change in the infiltration rate depending on the use of the HVAC system [51]. Like the blower door test, a tracer gas test should be completed at regular intervals to help determine any changes in building leakiness.

Natural Ventilation Sensors

Natural ventilation is the ventilation that occurs in a building due to the opening of doors and windows. This is different from mechanical ventilation, which is related to the HVAC system.

There are few ways to account for natural ventilation in a building but only one measurement is permanent and not intrusive. The sensors used to measure natural ventilation must be non-intrusive as natural ventilation occurs in the exterior doors and operable windows; if the sensor obstructs the movement of the building occupants it will be seen as a nuisance and is more susceptible to damage. Keeping this in mind, the most effective way of measuring the natural ventilation in a building is through proximity sensors on the doors, and using empirical correlations. Proximity sensors work by having two small magnets on opposite sides of the door that are in contact when the door is closed. When the door is open, the connection is broken and a signal is sent to relate this information to the system. This type of sensor can typically be observed in home alarm systems. and the using a small magnet. The equation that controls natural ventilation is:

$$Q = C_A A R_p \tag{19}$$

where, Q is the rate of air flow out of the building, C_A is air flow coefficient which is dependent on different factors for the door and the opening. These coefficients have been empirically determined for different configurations of door and can be found in ASHRAE Fundamentals. A is area of the door opening, and R_p is a pressure factor which is dependent on the stack effect and wind speed, as discussed earlier in this report. By measuring the amount of time the door or window is open, and by knowing the temperature difference between inside and outside, the amount of energy lost can be determined through the advection heat transfer equation. The amount of the way the door is open can be assumed to be 100% if automatic sliding doors are used. For swinging doors an approximation must be made. The amount that a window is open will be unknown but observations can determine an estimate for the amount it is open. The length of time the door will be open for will be determined by the proximity sensors installed in the doorframe [22].

Shading System

Shading is an important factor to measure to help determine the solar energy gain. It can also be used to help with correlations between building energy use and shading percent, which can increase the amount of useful controls in a building. To adequately measure shading there are two options that were proposed and need to be further developed for this research project. The two methods are integrated photodetectors and the use of image processing.

The photodetector method involves creating an array of photodetectors on each face of the building. The photodetectors would be installed to the surface, evenly spaced so that each photodetector would measure the shading on a small area of the building, each would also have an individual tag so that their position would be known. Each sensor would be the wired to the DAQ system. The signal from the sensors would be fed into a program that would then be able to estimate the amount of shading on the building. The upfront costs of such a system are large, especially when considering installation and wiring costs. It is also difficult to install the photodetector sensors onto windows and doors. Finally, as there are many smaller parts to this system, the reliability is low, as any malfunctioning sensor will adversely affect the accuracy of the system.

Using image processing software appears to be a much more attractive option. The system would consist of a series of cameras that would be capable of monitoring each surface of the building. The signal from the cameras would be sent to a computer that would process the signal. The image processing software is capable of determining which areas of the building are darker and also the different materials on the building envelope, such as the difference between the walls and the windows. Once all effects have been taken into account, the system can then accurately determine the amount of direct solar energy impinging on the building. If the outside environment is accounted for correctly the reliability for this system is expected to be good, as there are no moving parts and cameras generally have a long lifetime The cost is significantly less than the photodetector array and if a macro can be created for the image processing software the system is completely autonomous. Based on discussions with different software providers, the accuracy of image processing is high as these types of software are used for research and processes where accuracy is essential.

2.5 Literature Review Summary

This literature review first looked at the current state-of-the-art in regards to current research and standards. It was determined that while a significant amount of research has been done to infer an energy balance, there has yet to be a research project that measures a completed energy balance on a full scale building. The current standards also only focus on energy that can be consumed, stored, generated, and purchased. It can be seen that there is a need for a sensor array capable of completing full energy balance on a building and this type of research has yet to be completed.

The energy flows required to be measured in order to complete a full energy balance were then discussed. It was determined that for each of these energy flows it is well known which values are required to be measured. This leaves little uncertainty in the measurements chosen to be important for the purposes of this sensor array.

The types of sensors capable of completing these measurements were then discussed with their advantages and drawbacks listed. In Chapter 4 these will be weighed against each other using a decision matrix to determine the best suited sensor for each project.

3.0 Energy Model

The first step in the proposed process to develop the energy monitoring system is to complete a predictive building energy model to provide an estimate of the primary energy transfer within a building. The energy model can give important information on difficult to measure energy flows. These flows include solar heat gain, conduction through the thermal envelope and infiltration. The energy model can give information to help determine measurement range, locations and quantity of sensors that are required for the sensor array. It can also give useful information for the uncertainty analysis by giving likely values to be used in the Monte Carlo error analysis.

3.1 Review of Energy Models

There is a wide variety of energy models and modelling software that are capable of completing different tasks. These different types of models will be discussed to determine the most effective energy model for this step in the process.

The most effective model for this application is one where there is a high degree of accuracy and one where the accuracy of the software has been verified by a third party. There also needs to be a high level of detail as this energy model will need to mirror the proposed sensor array. This means that the information should be able to be broken down into smaller parts of the building and not just show the energy consumption of the building as a whole. For future consideration, the energy modelling software should be relatively easy to use and cost effective to be less restrictive to other people who may wish to implement this system. It would be a benefit for there to be a good user interface in addition to pre-programmed energy standards so the user can design the building quickly and accurately.

3.1.1 Level of Detail

An energy model may have highly detailed inputs and outputs. These energy models are considered to be calibrated and they attempt to have a high degree of accuracy when predicting the future results of the building energy footprint. A calibrated model attempts to replicate the building and its systems using modelling software. It also attempts to predict the scheduling of the systems and number of building occupants. The heating and cooling zones of the building are also accurately defined relative to the HVAC system design.

Harmer and Henze utilised calibrated energy models to predict building energy and to help with the commissioning process [52]. They developed an energy model using OpenStudio and EnergyPlus and utilised the RunManager and AnalysisDriver tools to complete a Monte Carlo Analysis to determine the accuracy of their model when compared to actual measured data. Weather data from two nearby weather stations was utilised in the simulation. The parameters of the model were altered to match the known values for electricity and steam consumption. These values were compared to actual building data for a period of 70 days and it was found that there was significant difference in the predicted and actual energy usage, deviating as much as 30% in electricity usage and 20% in steam usage on a daily basis. The parameters of the model were again altered so that the predicted energy consumption from the model would match the already known energy consumption of the building. After this was completed, the model was described as "perform[ing] well when compared to the actual data" [52]. This study identifies the main shortcoming of calibrated energy models. They can give general trends in building energy usage, but even when they are highly tuned to energy consumption data after the fact there is significant deviation from the predicted energy to actual energy usage. This can be attributed to many different factors that make the energy consumption of a building unpredictable.

Raferty et al. completed a study where the used a calibrated model to determine the hourly electrical consumption of the building. By utilising the hourly data from 2007 and a detailed model in EnergyPlus they were able to accurately predict the electrical consumption for 2008 within 8% [53]. While they were able to showcase the predictive power of energy models, it also shows the limitations of a calibrated model. In order to reach the high degree of accuracy a full year's worth of data was required. As the proposed energy monitoring system is a permanent fixture in the building, it must be developed during the building construction phase. As such, it is impossible to have measured data on building energy consumption before the building has been constructed, which makes it impossible to integrate a calibrated model into this methodology.

Alternatively, an uncalibrated, or "shoebox model", can be utilised. A shoebox model uses a simple representation of building geometry and zoning strategies to understand the general trends of the building energy footprint [54]. These types of energy models aid in the decision making process. They can be used as a comparison when determining the use of different energy efficiency features or attempting to reach a specified energy intensity. These models are popular to utilise during the design process. In the case where there is uncertainty in different design decisions, the building code or an ASHRAE standard can be utilised to fill in the gaps in knowledge. When designing an energy efficient building, ASHRAE 90.1: Energy Standard for Buildings except Low-Rise Residential Buildings is considered the benchmark standard. In North America it generally has more restrictions on material choices and air quality standards to improve the energy consumption and occupant comfort when compared to current building codes [55].

Shoebox models are less accurate than a calibrated model when both are completed after the design of the building. However, at the beginning of the design process when there is no data to help calibrate the energy model, this is not the case. In addition to this, it takes substantially more resources to utilise a calibrated model which can increase the cost of the building design process. Since a shoebox model is generally completed at the beginning of the design phase, the creation of a calibrated model introduces a new step in the design process, lengthening the time of the design phase.

3.1.2 Energy Modelling Software

The US Department of Energy lists over 140 different software packages capable of completing an energy simulation. Of these different packages the most commonly utilised ones for complete building energy analysis include EnergyPlus, eQUEST, ESP-r, and TRNSYS [56].

ESP-r and TRNSYS are the two most robust energy simulation tools on this list. ESP-r utilises a component-level approach where technologies and building spaces are assembled and represented by one or more control volumes. The control volumes are constrained by a mathematical energy balance based on the conservation of energy. These control volumes are the subjected to different controls, such as actuating a valve to meet a specific temperature set point [57]. An array of equations that describe the thermal energy transfer is then created and the program utilises an iterative solver to reach convergence to solve for temperature of each volume. The desired information, temperature, electrical consumption etc., for each time step is then given as an output to the user.

ESP-r performs well when modelling thermal interactions within a building. The system is robust with what can be accomplished when looking at thermal interactions; however ESP-r requires a significant number of inputs by the user. Also, there are few components in the ESP-r library and there is little documentation. Meaning when the energy model is being created, the user will have to create a large number of the components and systems in the building. These components and systems must be programmed into the simulation by the user, significantly increasing the amount of time to complete the simulation. This also requires that the user must have significant knowledge of programming and expert-level knowledge of the systems in question. This causes a steep learning curve, specifically when it pertains to building systems and the interactions between different systems [58]. ESP-r does not have a robust solar radiation routine and again, one must be programmed by the user into the code of the software. The ESP-r software is not optimized to add new routines into the library. The current course of action being taken in the current research is not to improve the ESP-r library, but to combine it with different programs that are better at simulating systems and sunlight [59]. ESP-r is a program that is capable of modelling thermal interactions; however this software does not adequately describe the systems of a building and does not adequately account for sunlight. This allows for certain aspects of the model to be accurate while others are inaccurate. As this application requires accuracy in all aspects of the energy model ESP-r is also not a good selection for energy modelling a building.

TRNSYS utilises a library of components that are able to be parameterised and connected to each other to simulate a transient model of different systems. TRNSYS utilizes a successive substitution solver, where the outputs of given components become the inputs of others. The components are such that they can create a multi-zone structure with inherent HVAC systems. These can be utilised to simulate the building energy [60]. TRNSYS possesses a large number of building systems that can be easily altered by the user. However TRNSYS was developed as a program to model solar hot water collectors. As such, the program is not adept at dealing with building physics, such as conduction through the thermal envelope [59]. As such, this program has the opposite problems of ESP-r where the program is good with systems and solar energy, but it lacks the ability to complete the complex thermal interactions within a building. Due to the inability of the program to accurately detail the thermal interactions in a building, the resultant simulation of an entire building may never converge. This will also negatively impact the results of the model, and by extension the design decisions as large sources of error can occur. This allows for certain aspects of the model to be accurate while others are inaccurate. As this application requires accuracy in all aspects of the energy model TRNSYS is also not a good selection for energy modelling a building.

Methods have been utilised to combine the two simulation packages so that each package is capable of playing to its strengths [59]. However, in order to get usable results, the user must have access and the knowledge to use both software packages, as well as the co-simulation package. While the TRNSYS systems may be utilised, as mentioned above, the use of ESP-r still requires a significant understanding of coding. Furthermore, the program that is being developed to co-simulate with the two programs is still in development.

eQUEST is one of the most popular energy simulation tools with around 10,000 downloads annually. The user creates a building model using a GUI and defines the inputs for different building parameters. The default inputs are based on the California Title 24 energy code but there are other sources of information in its library, such as ASHRAE 90.1. eQUEST utilises the DOE-2 engine which was developed by the US Department of Energy and is being constantly updated and verified by third parties. It has a simple user interface to allow anyone to utilise the software. eQUEST is a quick and has a focus on building energy which makes it a narrower product. This allows for a faster learning time and improves the ease of use when compared to ESP-r and TRNSYS. The conduction to the ground as well as infiltration modelling is simplified. Currently, the user is unable to customize any of the source code without recompiling the code, making it difficult to create any new building systems that are not in its library. This makes completing an energy model of any new building difficult as the required technology for the building may not be able to be accurately modelled. This requires the user to utilize different methods for overcoming the limitations in the program, which can negatively impact the accuracy. For example, if the building has a thermal storage system and eQUEST's library does not have a thermal storage system available there is no way to accurately model this system. The user would be required to alter different parameters to account for the difference in energy transfer due to the thermal storage. By changing these parameters, other energy flows may be impacted, which results in a less accurate model. The maximum number of time steps of the program is limited to 8760. Which means for an annual simulation the smallest time step is limited to one hour [61]. In all, eQUEST is an option that could be considered for completing the energy model of the building. However, as the system cannot account for new technologies or systems it is not recommended for buildings that have new technologies which are not in the eQUEST library.

EnergyPlus is another popular energy simulation tool. It is a text based program where the user inputs the variables into a user interface which compiles the information into an ASCII file. The program then uses the DOE-2 engine to simulate the building energy. As such the engine is constantly being updated and verified by third parties. EnergyPlus has more accurate and detailed results than that of eQUEST [62]. The largest challenge with EnergyPlus is that by limiting the inputs to being text based, it is difficult to create the structure of the building. To improve on the inputs, there is a program called OpenStudio, which acts as a link between the EnergyPlus software and the SketchUp design interface. This allows the user to create the 3-D model of the building using the design tools in Sketchup then input the parameters in OpenStudio, creating a much simpler user interface. This gives EnergyPlus a higher degree of accuracy and customization than eQUEST. The learning curve is less steep than ESP-r and TRNSYS. In addition, EnergyPlus was specifically design to model entire buildings, and was designed to allow for new technologies to be implemented within the building energy model. This is important as it reduces the implementation time of the model during the design phase. The libraries in EnergyPlus include many different energy codes, including ASHRAE 90.1, a standard that may be used to determine the design of the electrical and mechanical systems of the building. This is important as it can help to reduce the design time as fewer inputs are required. Also, it helps to ease the modelling process at a time where little information is known about the building. If all that is known is that the building will be designed to a specific energy standard, then the EnergyPlus model can be completed with a high degree of confidence.

As stated above, the most effective model for this application is: one where there is a high degree of accuracy, the accuracy of the software has been verified by a third party, there is a high level of detail, and the software is easy to use. For these reasons at the current time it is proposed to use EnergyPlus with the OpenStudio plug-in to create an energy model for this energy monitoring system. It is also possible that for simpler buildings, eQUEST is a reasonable substitute.

3.2 Energy Model Details

As it is proposed to start the development of the energy monitoring system near the beginning of the design phase, the energy model must be completed at the beginning of the design phase as well. At this stage of design, there may be a large amount of uncertainty in how to complete the building energy model. As each building is different and building codes differ from location to location this section cannot go into specifics.

The surface area of the building significantly affects parameters such as solar heat gain, conduction and infiltration. The exterior geometry also significantly affects these parameters. As such, the building energy model should not be started until there is a good idea of the exterior shape of the building. For the development of this system, the interior layout is largely unimportant. Once the exterior shape, geometry and location have been decided, the building envelope should be replicated in the energy modeling program. Some building design decisions may have been made at this point, such as types of windows or R-value of the walls. These design decisions should be represented in the energy model as closely as possible.

In the event that there is incomplete information on the design of the building it is recommended that the design of the building should be assumed to be a specific building standard. In some cases that may be the building code, however, for new buildings it is recommended to utilize the standards found in ASHRAE 90.1[55].

To utilize the ASHRAE standard it first must be known which climate zone you are in, as there are different requirements for each zone. A summary of climate zone by region can be observed below in Figure 5. A summary of parameters that should be followed for the energy model can be observed in A. EnergyPlus also has a library of parameters that will default automatically to ASHRAE 90.1 which changes depending on the defined climate zone.

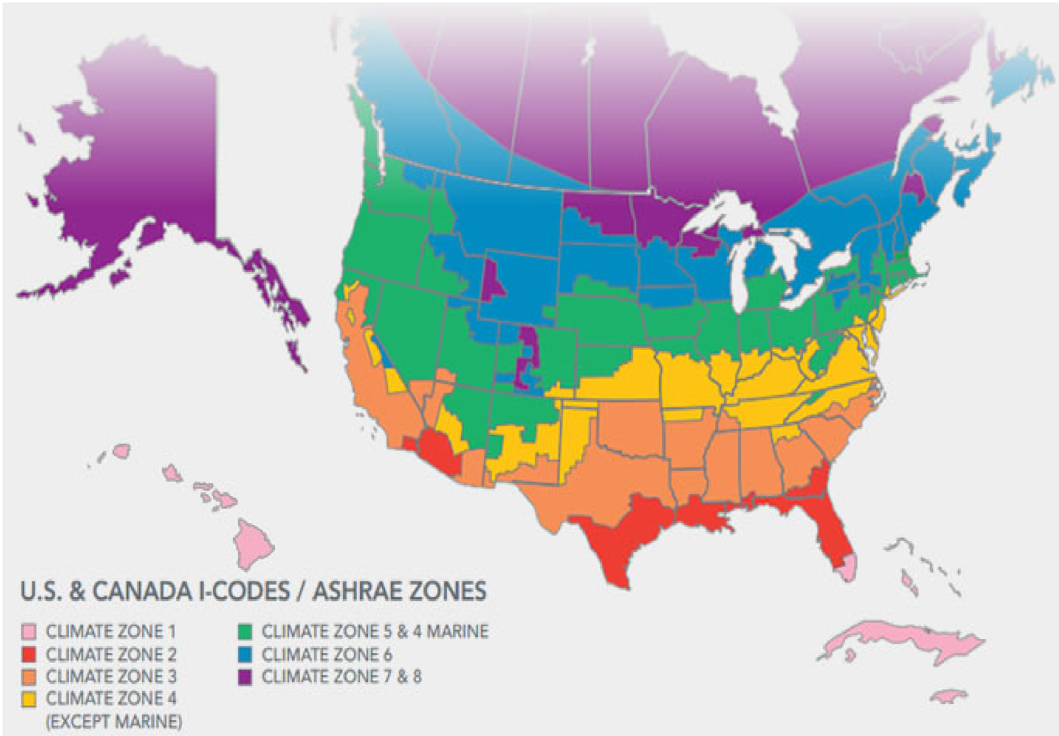

Figure 5: Summary of ASHRAE Climate Zones for North America

For this research project, an energy model was completed using EnergyPlus. The surfaces and sub-surfaces were created using SketchUp 2014 and the other relevant information, such as scheduling and material composition, was relayed to the energy model using OpenStudio. For the interior, it is recommended to create exterior zones that only have one exterior wall. This allows for each zone to only be dependent on one exterior surface, simplifying the solar gain, conduction, and infiltration energy flows. Each exterior zone should be 3 to 4 meters deep into the building with one large interior zone, as stated in ASHRAE standard 90.1 [55]. Furthermore, there should be a split between zones that are known to have different HVAC systems. An example of the proposed interior layout can be observed in Figure 6.

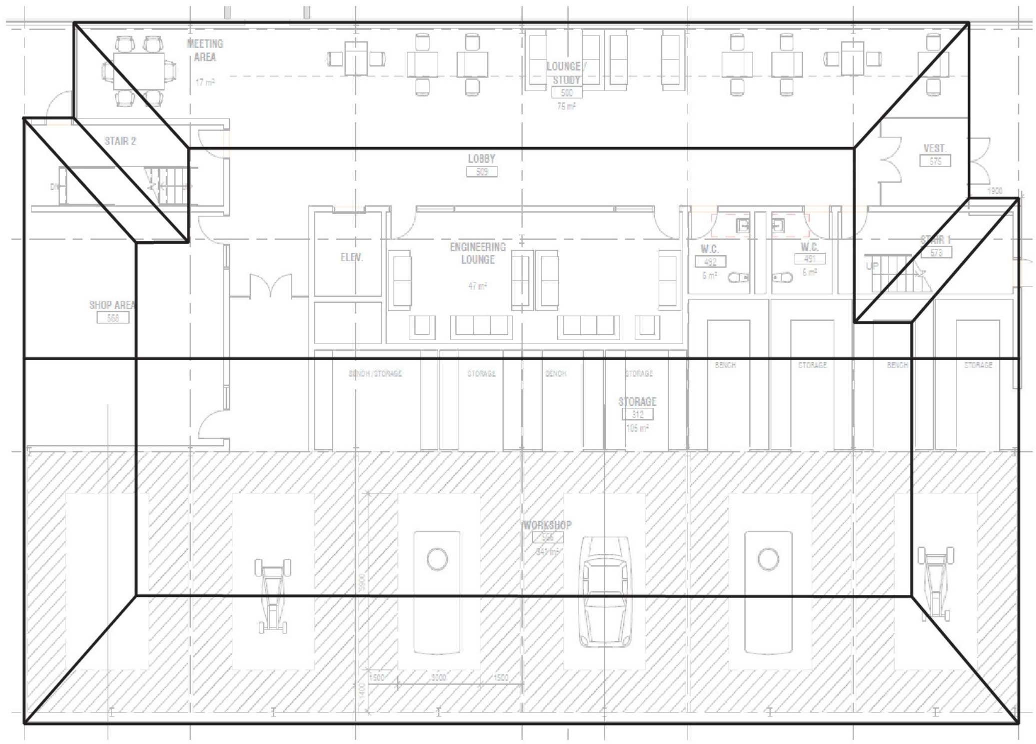

Figure 6: Layout of the First Floor of the Hatch Centre with an Overlay of the Zone Layout

As can be observed, each zone only has one exterior face. There is also a split in the middle as the front area uses a different HVAC system. More details on the energy model can be observed in section 5.1 and in Appendix A.

4.0 Methodology for the Design of the Energy Monitoring System

The development of the energy monitoring system involves five different sections. The energy model which was discussed in Chapter 3 was the first step. The remaining steps are ensuring an energy balance, selection of the sensors, installation guidelines of the sensors and finally the uncertainty analysis. Furthermore, the results of each step are dependent on some of the other sections. A summary of these dependencies can be seen below in Figure 7 where sections that are adjacent to one another are dependent on each other.

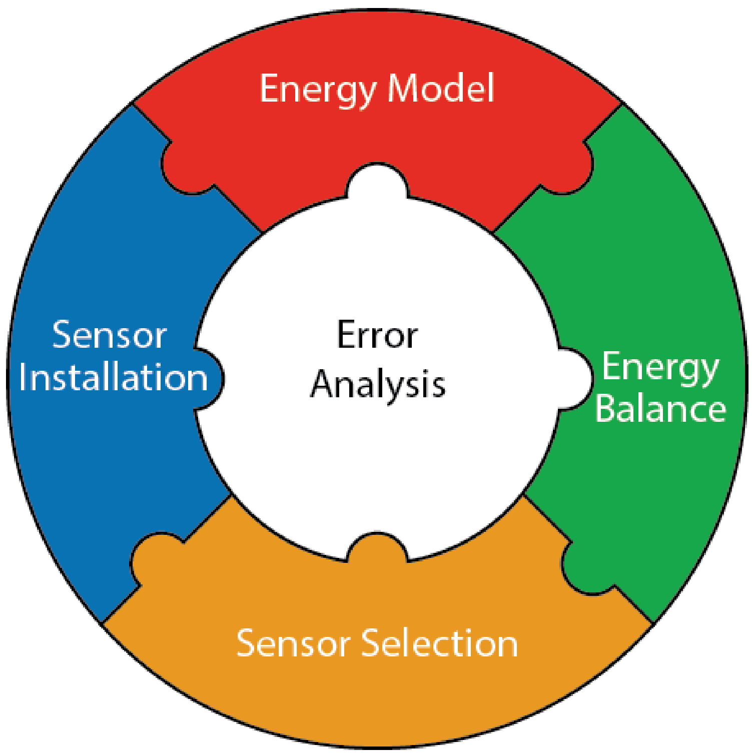

Figure 7: Schematic of Interconnected Dependencies for the Completed Energy Monitoring System

If properly accounted for, these linkages can improve the final design by enhancing each section that was investigated.

Some of the parameters mentioned below are not flows of energy but key performance indicators for buildings. Parameters such as CO_2 level, relative humidity, and room temperature are identifiers of occupant comfort. It is important to include these energy flows as most commercial buildings are places of business and it is well known that poor occupant comfort results in low productivity. They can also be utilized as benchmarking tools for the building automation system. Other parameters such as shading, wind speed, and occupancy are not direct energy flows, but are used to calculate energy flows. The values from these parameters can help to modify other energy monitoring sub-systems in order to get a more complete estimate of the energy flow. For example, wind speed is not a flow of energy, but it does affect the estimate of the building infiltration rate, which is a flow of energy.

4.1 Ensuring a Complete Measured Energy Balance

In order to ensure that a total energy balance is being measured, it is required to identify what energy flows occur within a building. By ensuring that all of the energy flows are measured, the cost effectiveness and the accuracy of the system is increased. For example, while conduction through interior surfaces does occur with regularity in a commercial building, it does not immediately affect the balance of energy; as such it is not required to measure this energy flow. Only energy that is transferred through the thermal envelope will immediately affect the building energy balance.

The complete equation for a building energy balance is must be broken down into two parts, thermal and electrical. The thermal energy balance equation is [20]:

$$\Delta Q = \pm Q_{Generated} \pm Q_{Stored} \pm Q_{Latent} \pm Q_{Conduction} \pm Q_{Infiltration} \pm Q_{Ventilation} + Q_{SolarGain} + Q_{Occupants} + Q_{Electrical} \tag{20}$$

The relative values for $Q_{Generated}$, Q_{Stored}, Q_{latent}, $Q_{conduction}$, $Q_{infiltration}$, and $Q_{ventilation}$ depend on whether or not the building is in the heating or cooling season. The instantaneous ΔQ does not necessarily need to equal zero, as there is thermal mass within the building and the temperature of the building can fluctuate over time. There are other small energy flows that occur in a building as well, these can include cold domestic water entering a building or photons of light from the lighting system that exit through windows. These energy flows are typically considered to be negligible as their magnitudes are significantly smaller than the magnitudes of the energy flows mentioned above.

The electrical energy balance equation is:

$$\Delta E_{Electrical} = + E_{Generated} + E_{Purchased} + E_{Stored} - E_{Consumed} \tag{21}$$

For this equation, $\Delta E_{Electrical}$ must equal zero as for any grid the consumption must equal the generation, in the case where there is electrical storage the difference between the two must be stored.

While these two equations give the absolute energy balance of a building, some of the terms in the building are the sum of many different energy flows occurring throughout the building. For example, all of the solar gain does not enter the building at one location and must be measured in multiple locations. In some cases it is essential to measure these smaller flows to increase the accuracy of the sensor array, while in others a larger picture is required to improve the cost-effectiveness of the system. For example, the energy transferred throughout the building by the HVAC system could be measured at the air handling unit or the sum of the energy in the air as it enters each zone. However, since the sensors that measure the mass flow and temperature of air may be expensive, measuring this energy flow at the zonal level may increase the cost of the system. As a result, a higher level view of the energy transfer, such as what percent of the energy flow recirculates into the air handling units and how much is ventilated out of the building, may be sufficient. The design of this sensor array is always a balancing act between measuring what is relevant to the building energy balance and minimizing the costs of the array.

Determining where thermal loads specifically occur is more difficult due to the number of different modes of thermal energy transfer, thermal regions, differences within a building and the differences between buildings. In order to make building thermal energy transfer methodologies more standardized, the building can be compartmentalized into set of into individual zones. While the location of energy transfer in each building may be hard to predict, the locations of energy transfer in each zone can be accurately determined. The zones in a building can be broken down into external zones, zones where there is at least one external surface; and internal zones, zones with no external surfaces.

In an internal zone there is the energy entering from the HVAC system, the energy leaving to the HVAC system, heat loads from electricity, occupant heat gain, conduction heat transfer to other zones through the surfaces and convection heat transfer throughout the room. An external zone has all of these modes of heat transfer however there are more modes of heat transfer due to their external surfaces. There is conduction to and from the outside environment, solar heat gain through transparent surfaces, and infiltration due to openings and leakiness of the building. A summary of these energy flows can be observed in Figure 8 and Figure 9.

These energy flows are the same for the building regardless of orientation or location. It should be noted that different types of HVAC systems have different energy flows, for example a radiant in-floor heating system has vastly different energy flows from a variable airflow system. This stems from the fact that the heating source and the incoming fresh air are separated in the radiant heating system. In order to avoid any confusion, the energy flows that are unique to an external zone are displayed, as mentioned above, the same energy flows as an internal zone are still occurring. By understanding that these similar energy flows happen in a predictable and repeatable pattern throughout the building, a much clearer sense of where the energy transfer is occurring in the building takes shape.

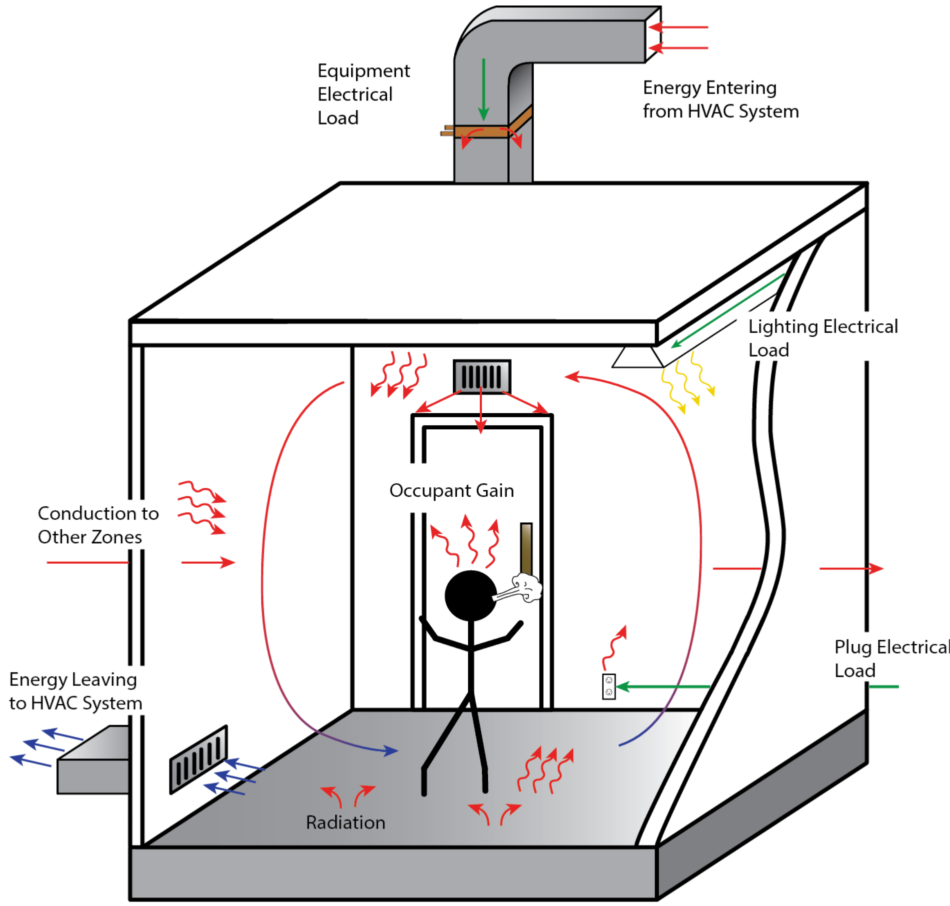

Figure 8: Diagram of Energy Flows in an Internal Zone for a Commercial Building with VAV and Reheat Coil

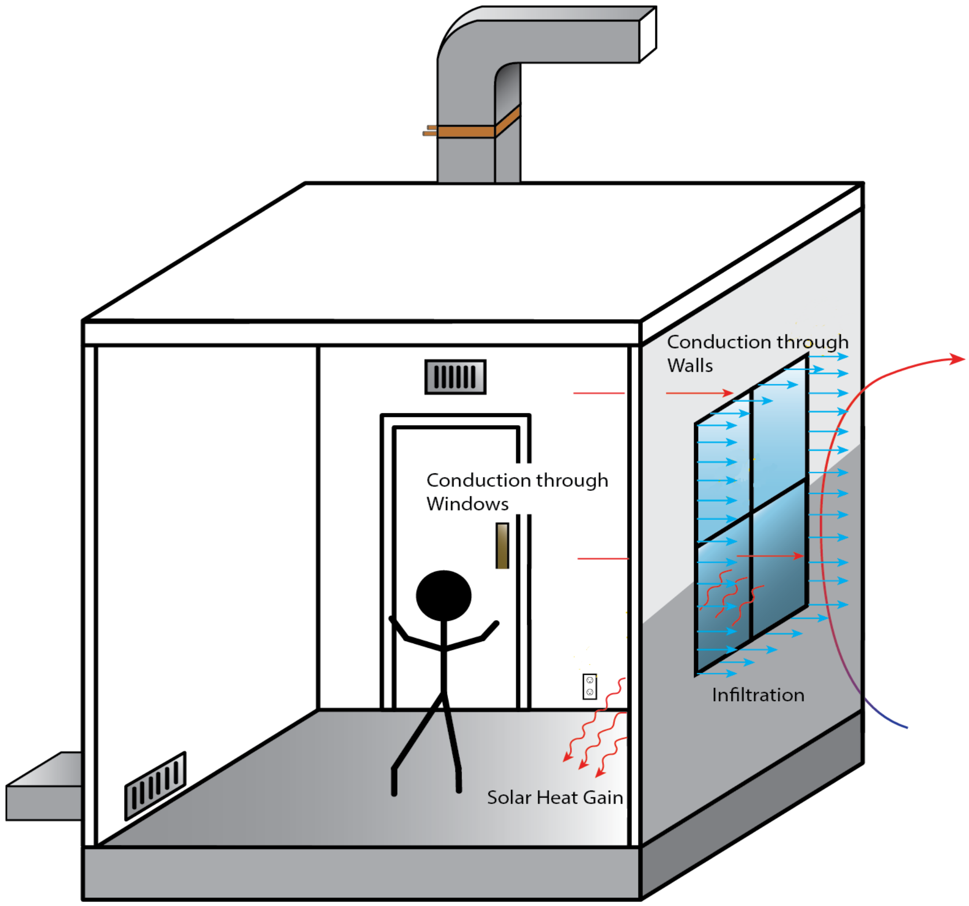

Figure 9: Diagram of Energy Flows in an External Zone for a Commercial Building with VAV and Reheat Coil

Along with the energy balance equation, the zonal energy construct was developed to ensure all energy flows were accounted for throughout the building. In addition to the zonal energy balance it is important to determine which energy flows are specific to the building and are outside of the zonal energy construct.

The zonal energy construct is based on a pre-existing knowledge of building energy use. In a building there are repeated patterns of specific energy flows. These modes are conduction through the envelope, sensible heat or cooling gain from the HVAC system, heating and cooling loss through the HVAC system, electric heat gains, occupant heat gains, infiltration and exfiltration, occupant heat gain and solar heat gain. These modes of energy transfer occur in a predictable way throughout the building. By taking advantage of this fact, a general idea of where energy transfer is occurring and the means of measuring that energy transfer can be created. It can then be determined where the sensors should be located throughout the zone to match the energy flows.

For a typical building with a VAV fan and a reheat coil for each thermal zone, the general locations of where the sensors should be located in an internal and external zone can be observed in Figure 10 and Figure 11 respectively. For all of the flows except for conduction, the location of the sensor directly corresponds to the location of the heat transfer. In the case of conduction, heat transfer is occurring on the entire surface. The exact location that best describes the mean conduction location could be determined with a computational fluid dynamics model; however, this location would only be correct for that model. Due to local effects acting on the surface, such as wind and shade from clouds, this location may shift throughout the year. As most energy models use the values for a typical year, what is modeled and what may occur could be different. For this reason, the location of the conduction sensor must be determined through secondary sources. This will not give an exact location, but a location which minimizes the systematic error of the sensor.

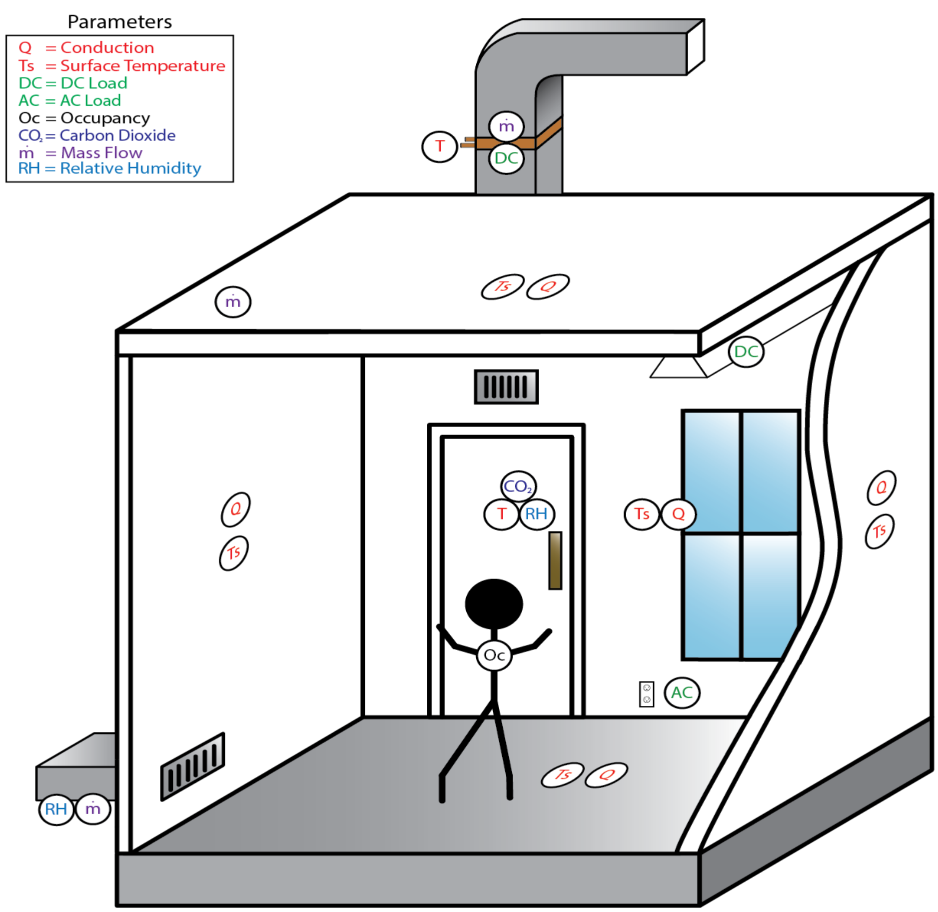

Figure 10: Locations of Sensors to Measure Energy Transfer in an Internal Zone with VAV and Reheat Coil

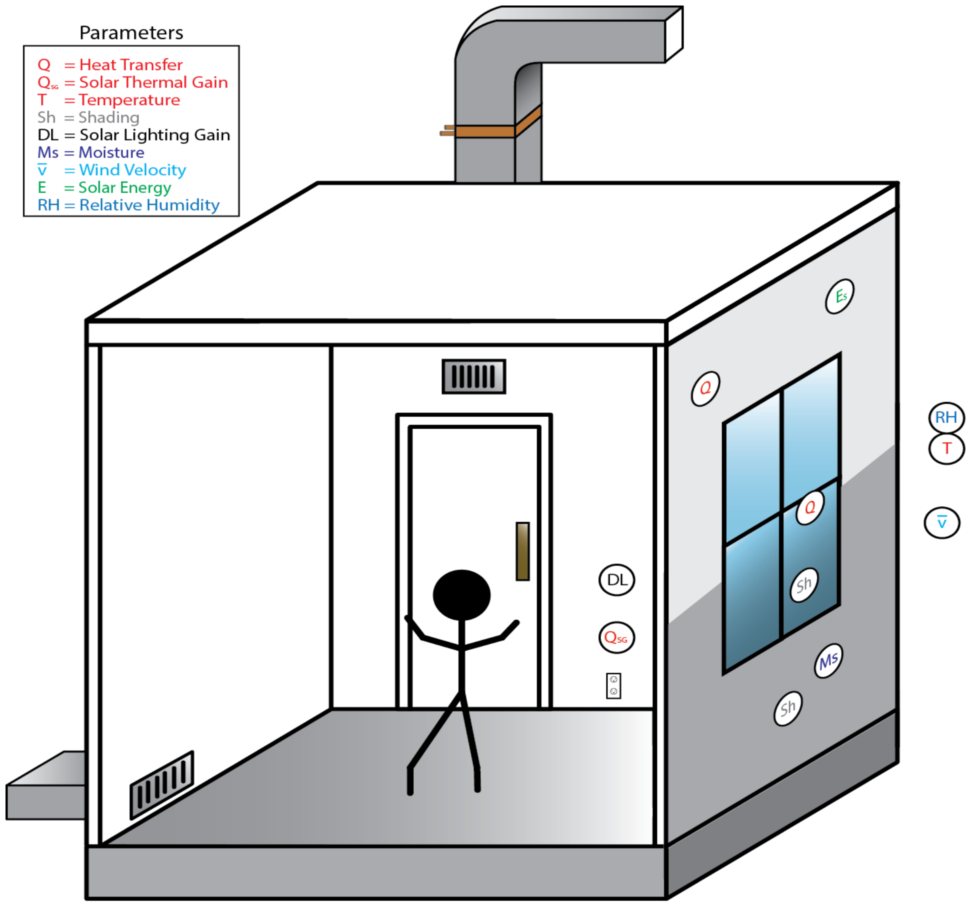

Figure 11: Locations of Sensors to Measure Energy Transfer in an External Zone with VAV and Reheat Coil

There are obvious limitations to the zonal construct. While it captures most of the consumed energy, it does not measure any electric or thermal energy produced and stored in the building. In order to mitigate these limitations it is important for the user to determine which sources of energy are specific to the building and determine adequate strategies to measure the total energy produced by these systems. For example, with a solar PV array it is important to measure the produced energy and any captured thermal energy that may be used in the building.

4.2 Sensor Selection for Specific Applications

After determining the specific energy flows in the building and their location, it is important to determine how the energy flows will be measured. There are many factors that go into determining which sensors are the best for each project and it is important to objectively determine which sensor is best given the context of the project.

As there are a multitude of individual sensors it is best to first judge the individual sensing characteristics. The basic characteristics of all sensors include: reliability, the time between failures of the sensing instrument and how it is suited for the expected environment; robustness, the time between calibration and maintenance in order to ensure data is accurate; accuracy, the difference in the measured value and the true value of what is being measured; and cost, which includes the initial capital cost as well as the installation cost [63]**.** To ensure the most fitting system for the project, these criteria should be ranked in order of importance for the specific project. Once ranked, the criteria should be given a score out of 10 to objectively measure the applicability of each sensor for the application. This can be done using the pairwise comparison method [64]. This method uses a matrix to compare each parameter to another single parameter to determine the importance. An example can be observed in Table 3 where the sensing parameters are being compared to reduce the lifecycle cost of the sensor array.

Table 3: Example of the Pairwise Comparison Method to Minimize Lifecycle Cost of Sensors

Parameter		A	B	C	D
Reliability	A	-	AB	A	A
Robustness	B	-	-	B	B
Accuracy	C	-	-	-	D
Cost	D	-	-	-	-

For each comparison, the sensing principle which is more important is placed in the cell in the matrix. In the event of a tie between the two parameters, both parameters can be observed in the cell. The more important factor can be determined through experience and when possible can be made by a group decision. By counting the frequency of the parameters in the matrix the overall importance of each sensing decision can be determined. This importance is then reflected in the weights of the sensors in the decision matrix. In this example, cost is more important than accuracy; reliability and robustness are more important than both. As cost is not unimportant, for this research project it was given a weight of 5 out of 10, the other parameters were then weighted according to the results of the comparison.

There may also be extra criteria that must be met in order for the sensor choice to make sense. Criteria such as environmental factors, size constraints or any other project specific factors can be used to eliminate different types of sensors and help to determine the most effective sensor.

Once the relevant characteristics have been chosen and ranked and the project critical parameters have been identified, the next step is to research each type of sensing principle so that the different types of sensors can be objectively compared to one another. For example, when measuring temperature, the different types of sensors are thermistors, thermocouples, infrared measurement, and RTDs. As described in detail in section 2.3, thermocouples are inexpensive and reliable but they need to be frequently calibrated, approximately every year. Thermistors are more expensive but require less frequent calibration and are more accurate [25]. RTDs are accurate and require even less calibration but are expensive, in the \$20 - \$50 per sensor range. Each sensor is compared to a reference design, a baseline sensor that meets the minimum criteria decided to be an adequate sensor. For this decision matrix meeting the reference design scores a 5, with an increasing or decreasing value based on the performance [65]. For the temperature sensors, the reference design would be a sensor that required calibration once every two years, has an expected lifetime of 10 years, can be submerged in water, has an uninstalled per unit cost of \$25/sensor and has an uncertainty of 2% full scale. A sensor such as this would have a low life-cycle cost while still maintaining uncertainty levels which are acceptable for this system. A summary of how each principle compares can be observed in Table 4.

Table 4: Sensor Decision Matrix for Temperature Sensors

Factor	Weight	Thermistor	Thermocouple	IR	RTD
Robustness	9	7	5	5	8
Reliability	9	7	8	9	7
Cost	7	6	8	2	3
Accuracy	5	8	7	5	9
Score		**210**	208	172	208

As can be seen from the above table, each sensor has its advantages and disadvantages. Based on the weighted scores determined through the pairwise comparison and the reference design, the best sensor to use is a thermistor. The weighted scores for each parameter are based on the knowledge of the person using the decision matrix. Different projects may have different priorities, for example accuracy may be determined to be the most important parameter. Other parameters not mentioned here may also have an importance. As such, the ranking system may change from project to project, and different sensors may be selected.

The use of a decision matrix can simplify the sensor selection process and creates an objective way of choosing between different types of sensors. The usefulness of decision matrices is limited to the skill and knowledge of the user. Without any prior knowledge of sensors, it may be difficult to determine what the correct weightings for each factor should be. It can also be difficult to choose the score for each individual sensor. However, if the due diligence is taken and the context of the project is kept in mind when making these rankings, the limitations of the decision matrix can be minimized.

A summary of all of the selected sensors can be viewed in Table 5. The selection of these sensors is dependent on their own decision matrix based on sensor details described in Chapter 2. The decision matrices for each sensor decision can be observed in Appendix B

Table 5: Summary of Selected Sensors for the Energy Monitoring System

Parameter	Sensing Principle	Location
Temperature (Air)	Thermistor	Bulk Air in Zone, Ducts
Temperature (Liquid)	Thermistor	Pipes
Volumetric Flow (Air)	Thermal Dispersion	Ducts
Volumetric Flow (Liquid)	Ultrasonic Flow	Pipes
CO_2 Levels	NDIR	Bulk Air in Zone
Electric Load	Non-Socket Electronic, Feed-Through Meter	At Load
Relative Humidity	Resistive Type	Bulk Air in Zone, Ducts
Thermal Conduction	Heat Flux Transducer	Exterior Walls, Exterior Windows
Solar Heat Gain	Silicon PV Pyranometer	Indoors, Window
Wind Velocity	Ultrasonic (2-Axis)	Outdoors
Occupancy	Optical Turnstile	Entrances
Infiltration (Building Leaks)	Tracer Gas Test	Bulk Air in Zone
Natural Ventilation (Building Openings)	Proximity Sensors	Entrances
Shading	Image Processing	Outdoors

4.3 Installation Guidelines for Sensors

In order to ensure the sensor array is working optimally throughout its lifetime, it is essential for the sensors to be installed correctly. The correct installation mainly helps to reduce the systematic error of the individual components of the system reducing the uncertainty in the total system. The systematic error is the error that is inherent to the system. Problems such as a heat flux sensor altering the path of heat transfer due to increased thermal resistance would be considered systematic error. These errors are always inherent in the system; however they can be reduced to minimum values if correct care is taken during the installation process. For the commonly measured parameters such as temperature and mass flow, the procedure that must be taken to decrease the systematic error is well documented in the technical literature, however for the less commonly measured parameters, it is required to look at multiple sources to better understand where this systematic error occurs, and how to minimize it. The correct installation of sensors can also help to increase the longevity of the system. This can be done by ensuring that the sensors are installed in a way that is consistent with their appropriate operating conditions.

Air Mass Flow

Thermal dispersion sensors were chosen to measure mass flow of air in the ducts. A thermal dispersion meter has a heated RTD and a non-heated RTD for the reference measurement. The temperature of the heated RTD will vary based on the flow of the air in the duct. There are two types of thermal dispersion sensors. One type measures the difference in temperatures between the two RTDs while the other type is controlled in such a way to keep the two RTDs at the same temperature. When measuring mass flow in this way, it is important to locate the sensors far enough from any obstructions or bends in the ducts. This ensures that the flow within the duct is fully formed minimizing any local heat transfer effects at the sensor. The recommended length for a thermal dispersion sensor is one diameter of straight duct [66]. It is also important to get an average bulk flow of the air in the duct by making multiple measurements inside the duct. ASHRAE guidelines recommend having a sensor density of 4 sensors per 0.09 m^2 of duct area [67][68]. When working with thermal dispersion sensors it is also recommended to ensure that there is minimal moisture in the air to avoid corrosion [69]. Any other specifics should be given in the sensor documentation.

Air Temperature

The chosen air temperature sensors are RTDs and thermistors, depending on where they are located. These types of sensors are generally more stable than thermocouples over the long term and their costs are decreasing to allow them to be competitive to a thermocouple. Both sensors work by changing the resistance of the material based on the temperature it is measuring. When a current is sent through the sensor, a voltage drop occurs that is dependent on the resistance of the sensor. This voltage drop is measured and the temperature is then known.

When measuring the air temperature in the ducts it is important to measure the temperature near the air mass flow meter. This is due to the fact that the same local effects than can alter the mass flow sensors can adversely affect the temperature measurement [70]. There is a potential to combine sensors as well, as in some applications the unheated RTD that is acting as a reference measurement can measure the temperature of the air as well. Some sensors also have built in tables that change the density and heat capacity of the fluid that is being measured. This allows for the heat transfer to be the direct output of the sensor.

It is also important to realize that in some scenarios the local air temperature may be measured in a duct without a mass flow measurement. Due to conservation of mass, the mass flow can be the same before and after an area where heat transfer occurs, such as in an ERV. By understanding where mass flow and temperature measurements are redundant, this helps to make the sensor array more cost effective.

Combined Air Flow and Temperature Sensor
There are a number of sensors that can simultaneously measure air flow and temperature in a system. Based on the results of the sensor selection the ideal sensor is one where the temperature is measured with an RTD and the air flow is measured with thermal dispersion.

The number of devices required in a duct is dependent on the duct size. There is a recommended density of sensors of 4 sensors per every 0.09 m^2 of duct area [67][68]. The correct number of devices should be securely fixed in the air duct in the correct orientation. Each device should have a dedicated transformer to power the thermal dispersion sensor and to record the data. The output of each device should be wired to a multiplexer, which will convert the electrical output to a known value. This electrical signal must be wired to the DAQ system for collection. There are no other installation restrictions on this type of device.

To accurately measure the total amount of energy put into the system, at minimum each device should be placed in the supply and return of the main HVAC system. For any air related heat transfer, such as in an ERV, the devices should be placed to adequately measure all energy flows in and out; for an ERV this would result in 4 devices being used to measure the sensible heat energy transfer.

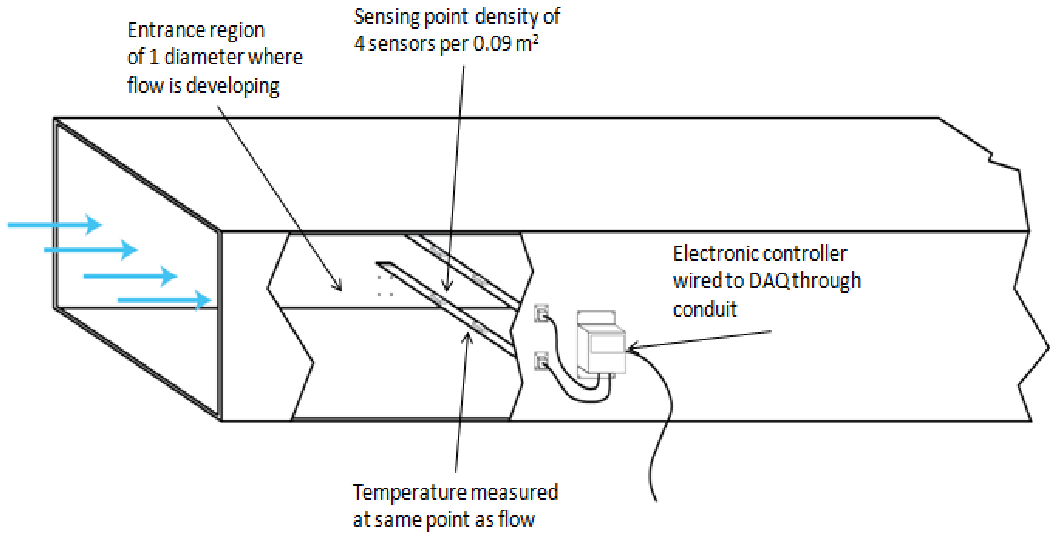

Figure 12: Installation for the Mass Air Flow in a Building

Liquid Flow

It was determined that ultrasonic flow meters would be best suited for this application. This was due to the long term stability of such sensors when compared to sensors that rely on a pressure difference. By being non-invasive the installation costs are also significantly less, which allows for a more cost effective sensor array overall. An ultrasonic flow meter sends an ultrasonic signal through the water to a receiver and the faster the flow of the water, the quicker the time from one node to the other will be. This transit time as well as knowledge of the density of the fluid allows for the volumetric flow to be determined.

While measuring liquid flow it is important to locate the sensors away from any disruptions to ensure that the sensor is in the fully developed region of the flow [71]. This is determined to be 10 diameters from any obstructions in the flow system. It is also recommended that the flow be measured upstream from where the heat transfer is occurring [71].

Liquid Temperature

The chosen liquid temperature sensors are RTDs. When measuring the air temperature in the ducts it is important to measure the temperature upstream of the liquid mass flow meter but close to it in proximity. This is due to the fact that the same local effects than can alter the mass flow sensors can adversely affect the temperature measurement [71].

There is a potential to for temperature and flow to be combined in a sensor so that mass flow is directly measured. Some sensors are also able to automatically vary the thermal properties of the fluid that is being measured. This allows for a direct measurement of the energy transfer from the working fluid. Using the same logic as measuring air flow and temperature, there is also the potential to measure the local liquid temperature without measuring the volumetric flow rate.

Combined Liquid Flow and Liquid Temperature

Like the air measurement sensors, it is possible to combine flow and temperature measurements for liquid heat transfer. The energy transfer of liquid flow is controlled through the temperature difference and the flow rate. The location of the thermal energy transfer is the same location where the flow of energy would need to be controlled. Because of this fact, it is then possible to help reduce the cost of the system by utilizing a combination liquid energy meter and control valve. Specifically, these types of valves are called energy valves.

The valves can be designed to work on either the return or the supply side of a heating or cooling coil. In order to determine how much energy is being introduced into the system two temperature sensors should be installed on opposite sides of the coil. If the surrounding pipe is being insulated it is important to keep the insulation to a thickness that does not encroach on the valve automation or the flow sensing equipment. The inlet must be in a straight length of pipe. The exact distance will be given in the corresponding installation manual. Any other specific installation instructions given in the manual should also be followed. The temperature and flow outlet signal should be wired to the DAQ system for data collection. There are no other restrictions for this type of sensor.

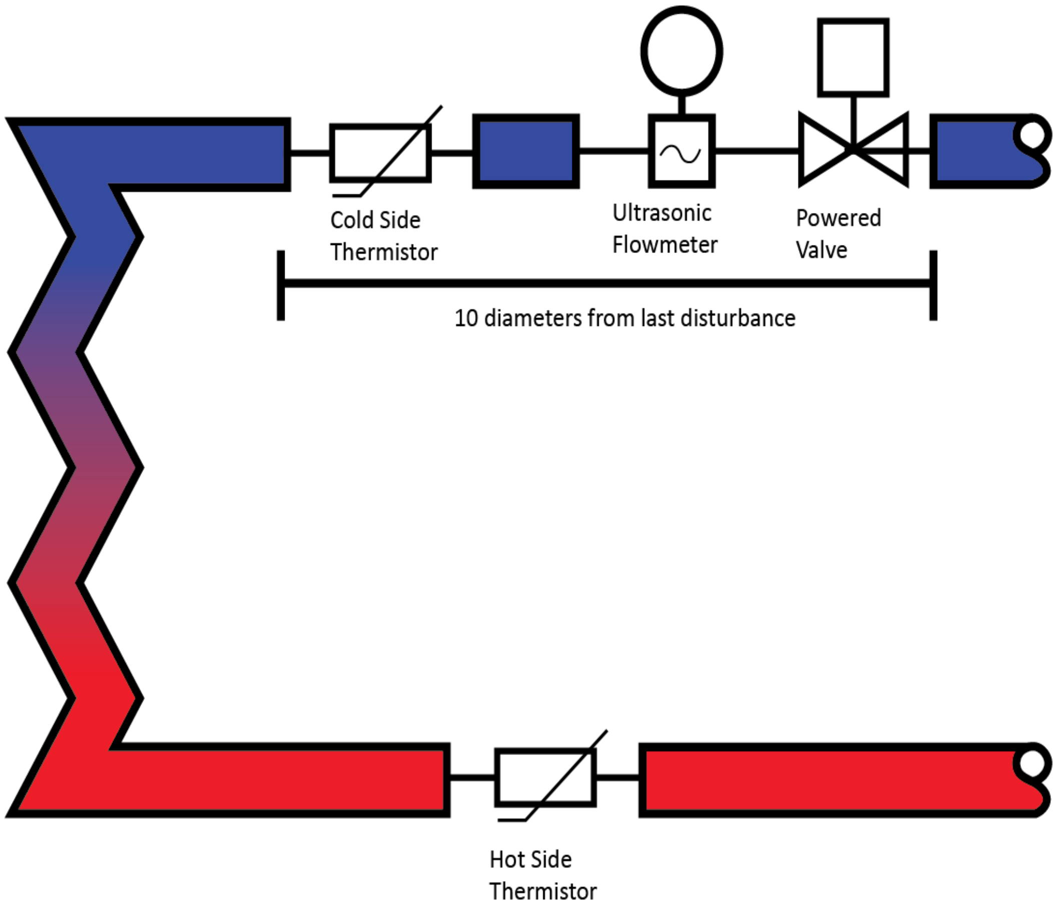

Figure 13: Schematic Diagram for Installation Liquid Flow Sensors around Heat Transfer Locations

Thermal Conduction

There is currently only one way to effectively measure thermal conduction and it is through the use of a heat flux transducer. The thermopile type heat flux sensor has thermocouple junctions connected to a thin constantan film sandwiched in the middle of the sensor. The junctions must be in contact with the hot/cold surface of the sensor and the thin film. As heat passes through the thermocouple junction and through the film it creates a small voltage proportional to the amount of heat penetrating the film. By grouping many thermocouple junctions the voltage can be amplified higher to increase the signal output.

This type of sensor is a passive sensor, due to the nature of thermopiles. In order for better measurements it may be ideal to equip two sensors in an area for averaging. This is recommended by the manufacturer but should be taken with a grain of salt as this parameter is not advised by the research and may be a strategy to boost sales.

There are a number of different measures that should be taken to reduce the systematic error of the sensors. First of all, the heat flux transducer itself increases the thermal resistance of the wall or window. It is recommended that the thermal resistance of the heat flux transducer be less than 0.45% that of the surface it is measuring [72]. The contact resistance of the system should also be reasonably small; a resistance measuring less than 0.1% of the measured surface is required [72]. In order to help reduce local effects at the wall it is recommended that a metal substrate be placed on the back of the heat flux transducer to help smooth out the heat flux signature going through the sensor [73]. In all, the total thermal resistance of the sensor and substrate must be less than 0.55% of the surface that is being measured. To aid in the reduction of the contact resistance an epoxy is recommended between the surfaces that will be in contact [74].

In addition to the thermal resistance of the sensors it is important to use a larger sensor to get a better average of the local heat transfer that will be used as an indicator for the heat transfer of the entire surface. The recommended minimum size for the HFT area is 500 mm^2 [72]. Finally, the emissivity of the surface when compared to the surrounding surface can also affect the measurement of the HFT. The HFT and the transducer should be the same dark colour to ensure that the emissivities are the same and HFTs with similar optical properties of the wall should be used when possible [72].

When measuring the heat flux through a non-opaque surface, such as a window there a few more sources of systematic error that should be taken into account. There is the possibility of the sun heating the HFT which requires some solar shielding. To reduce the error a shield should be placed between the sun and the heat flux transducer. To account for the decreased thermal resistance in windows it would be advantageous for the solar shield to replace the conductive substrate. Therefore, the material must have a high thermal conductance, a high emissivity and a small thickness. The ideal material for this purpose would be is aluminum foil. To further reduce the thermal resistance of the system, using a HFT that can be Glass also has a high emissivity so ensuring that the HFT on the window has the same emissivity is essential to reducing the systematic error of the sensor.

When installing the heat flux transducer to measure the conduction through the window there are a few slight changes that should be made. As there may be a pyranometer to measure solar gain through a few select windows it is important to not interfere with this measurement, because of that it is recommended that the heat flux transducer be positioned one foot from either the top or bottom of the window. The aluminum substrate must also be much thinner as windows have less thermal resistance. The thickness of the substrate depends on both the window properties and the sensor properties.

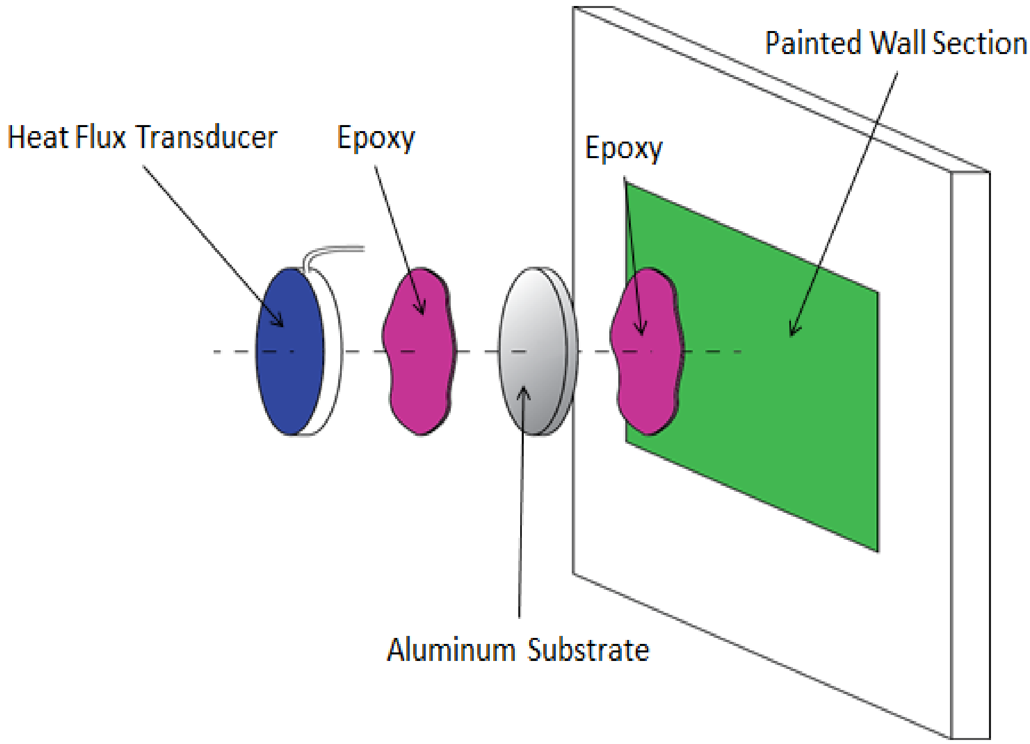

Figure 14: Recommended Heat Flux Transducer Installation on a Wall

The heat flux transducers should be installed on the exterior wall of the zone and on the exterior window where it is predicted that the internal and external conditions will be different. This is dependent on many factors and involves the best judgment of the reader.

The conduction measurements are also point measurements that must be expanded to the surface being measured. It was shown section 4.1 that conduction occurs out of the building on each exterior face, through the walls and windows. The rate of conduction is different for each. For this reason it is required for a heat flux transducer to be installed on the exterior wall or window of the room in the building. For cost purposes it is proposed to only use one sensor for each wall. This one sensor, if installed correctly, will give an accurate representation of the conduction over that entire surface. The effect of thermal bridging is difficult to determine in a building as it is dependent on the insulation level of the surroundings. There is a linear correction factor that can be completed. The equation is:

$$Q_T = Q_m A + l\Psi\Delta T \tag{22}$$

Where l is the length of the thermal bridge element and Ψ is the linear heat loss coefficient [75]. If the building has been designed to eliminate the possibility of a thermal bridge this step is not required to take as it can be assumed the effect of thermal bridging in this scenario is negligible.

Once the building has been completed, it is possible to take an IR picture of some of the exterior walls to determine the amount of thermal bridging that occurs in the building. If there is limited thermal bridging than there is no need for a correction factor, however, if there is a large amount of thermal bridging a correction factor may need to be used or the thermal bridge should be fixed.

Solar Heat Gain

The most effective way to measure solar energy is by use of a pyranometer. A pyranometer is a large thermopile that is sensitive to certain wavelengths due to the coating on its protective lens. When solar energy is incident on the front face of the thermopile it heats up and a current is generated. The current corresponds to the total solar energy that is being measured.

The equation for solar heat gain is given as:

$$G_{solar} = A_w \times T \times S \tag{23}$$

The size of the window is known and if the solar flux can be measured on the inside of the window it will implicitly take into account the window dependent factors.

In other studies it has been confirmed that the sunlight entering through a window is in the range of 400 to 1100 nm [76]. This allows a pyranometer that has a smaller range to be used in the energy monitoring system reducing the cost of the system. The pyranometer should be placed as close to the window as possible, within 20 cm, as, generally, the intensity of light decreases as the distance from the window increases [76]. The pyranometer should be from 0.8 to 3 m from the floor to reduce the reflected light from the floor interfering with the measurement. The pyranometer must be mounted so that its face is perpendicular with the window [76][77]. As the pyranometer only has an 180° view it is not required to protect the pyranometer from light that is reflected out of the room or from light fixtures.

To permanently install the solar heat gain measuring system it is recommended that one pyranometer will be installed facing each direction that the building will face. Based on the building energy model, without any shading mechanisms there is no preference for where the sensors should be placed, but to avoid inadvertent shading it is recommended that the sensors be placed on the third floor. To avoid any accidental damage to the sensor it is recommended to install the sensor at the top of each window. Observations will ensure that the correct location on the top of the window is determined. A summary of the installation can be observed in Figure 15.

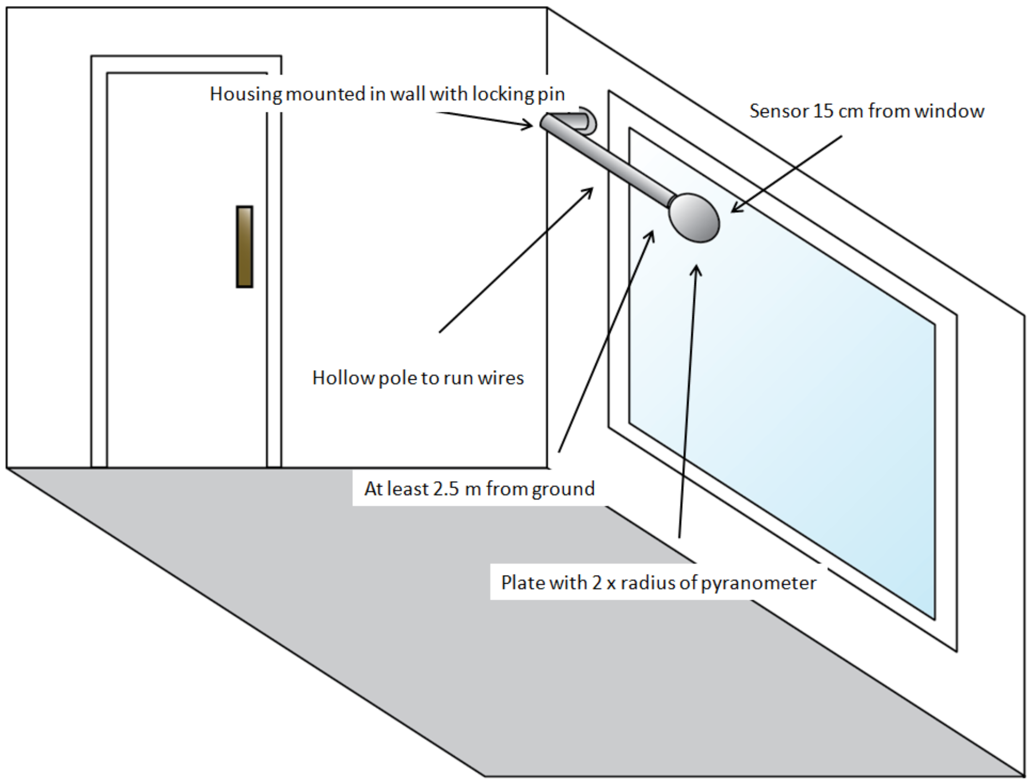

Figure 15: Installation Summary of Pyranometer for Heat Gain Measurement System

As Figure 15 shows, the pyranometer is mounted horizontally on a shielding plate. The plate is attached to a hollow metal pole at least 1 m high. The pole will slide into a housing unit embedded in the floor which is 6" from the window. The housing unit and the pole will have a hole drilled in them and the holes should line up for a locking pin to secure everything into place. This housing should be designed so that the pyranometer face is perpendicular to the window. The wires should run to a connector at the bottom of the housing unit so that the pyranometer can be removed temporarily without cutting the wires or destroying the wall. The wires from the sensor should then be run through the adjacent wall to the access conduit of the building. This proposed setup will accurately measure the direct sunlight coming in through the window. Observations must be taken before the sensors are installed. These will help to ensure that the pyranometer readings are always in direct sunlight, unless the entire face of the building is shaded. If one pyranometer is unable to meet these capture the nominal shading it is suggested that additional meter be installed based on a shading study or by using modeling programs such as Shading II [78].

Steps must be taken to expand these results to each other window facing the same direction. Surfaces must also have the same optical properties; if this is not the case a pyranometer is required for each different set of optical properties. There must then be a shading monitoring system in place that is capable of determining where the building is shaded and can automatically correct for the shade on other windows that are being represented.

Shading

While it is possible to measure the solar energy entering each window, pyranometers are an expensive sensor and alternative methods to measuring the total solar energy of the building should be discussed. One way to reduce the cost is to measure the amount of direct and indirect sunlight that is entering the building. As can be observed in Figure 16 the sunlight entering a building can either be direct sunlight or diffuse sunlight, depending on how the building is shaded. If the energy in the diffuse sunlight, direct sunlight and where these regions exist are known, it is possible to accurately measure the amount of sunlight in a building.

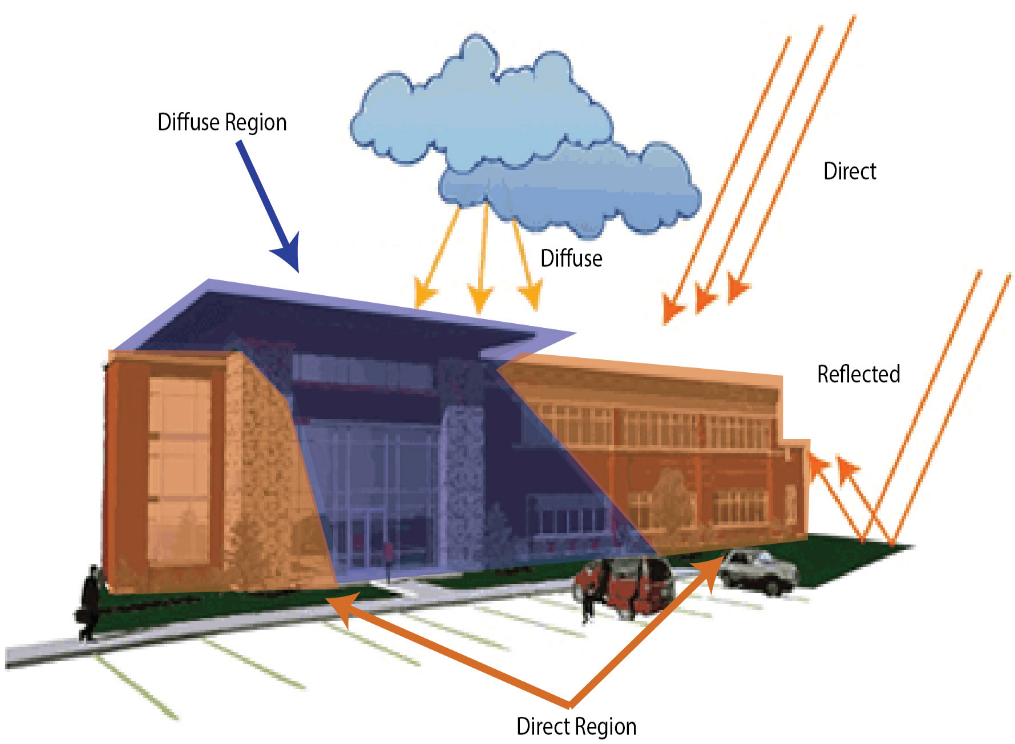

Figure 16: Areas of Direct and Indirect Sunlight on a Building

Currently, building shading is not a measurement that is typically done. Most research projects have focused on confirming shading models and determining reduction in energy use. These research papers use direct observations of shading as opposed to autonomous measurement [79][80]. A simple way to measure building shading involves the use of image processing and a direct video feed. From our daily observations, a building that is shaded is darker than when it is not shaded. Image processing software can measure this change in grey scale to determine where the building is under indirect sunlight. The next step is to use the software to determine where different materials are. As shown in Figure 17, a building has many different materials and a baseline calculation is required so the software can determine where the sun is entering the building. By overlaying the regions in Figure 16 and Figure 17 it is possible for the image processing software to determine whether direct sunlight or diffuse sunlight is entering the building. By making this distinction and having values for the energy of both direct and diffuse sunlight it is possible to determine the total solar gain of the building with minimal pyranometers.

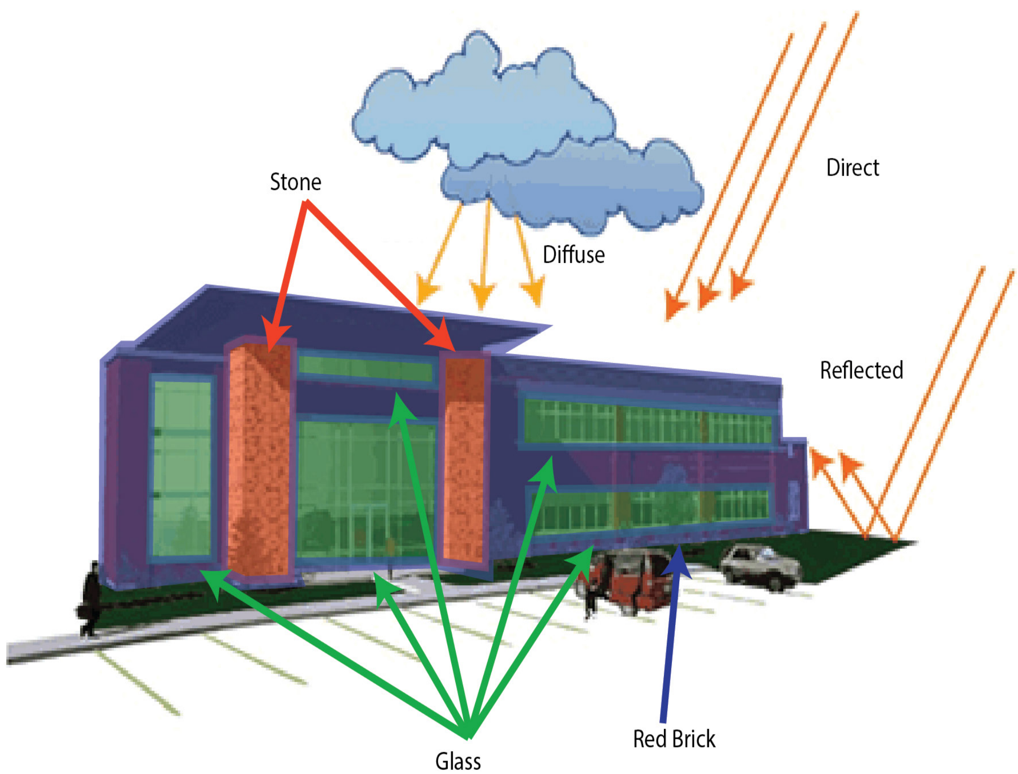

Figure 17: Areas of Different Materials in a Building

The systematic error of this system is currently unknown, as the testing of this shading measurement system is considered outside the scope of the research project.

The second half of the solar heat gain measurement system is the device that measures the percent of each building face that is under shading. The proposed system will use image processing to determine which surfaces are under shading and which surfaces are under direct sunlight. This will be done through manual calibration of the software, by manually determining the values when a surface is under direct sunlight as well as manually determining the corresponding material to where it is located in the image. A macro will then be created to automatically input an image, process the image and output the results.

In order to capture the image of the building, a number of cameras will be required to capture images of each surface. The cameras should be housed in surrounding buildings or a weatherproof container that will protect the device from the expected elements. The cameras will need to be hard-wired or wirelessly connected to the computer that will be completing the image processing analysis.

In order to accurately measure the solar heat gain of the system another program will need to be written to determine which percent of windows are shaded on each surface. By measuring the direct sunlight with the pyranometer discussed earlier, and by measuring the levels of indirect sunlight, an accurate value of the solar gain into the building can be determined. The specifics of this program have been determined to be outside of the scope of this project and more research is required to complete this section.

An alternative to this system would be to use shading software to model the shading on each surface. The solar heat gain can then be adjusted based on these numbers. While this does not directly measure the shading on the surfaces, it will still improve the accuracy of the solar heat gain energy flow.

Occupancy

There are many ways to measure the energy from occupants in a building. It was determined that to estimate the effect of occupants on total building energy was through the use of an occupant tracker system. The amount of heat gain would then be determined by estimating the watts of energy emitted by each occupant. While there is an increase in the uncertainty of the system, it is the most cost effective way of measuring this energy flow.

The proposed system is an optical turnstile. An optical turnstile works similarly to a physical turnstile, where occupants passing through it increment a counter to keep track of occupancy. Unlike a physical turnstile, an optical turnstile is non-invasive and is more difficult to be bypassed. The optical turnstile developed for this system utilizes a webcam and two strips of reflective tape. The webcam has an IR filter so that only heat signatures from the body are seen. When the heat signature passes the reflective tape, a program that is processing the webcam image determines whether the body is going in or out and increments the counter. By installing one turnstile at the entrance or exit to the building the total occupancy in the building can be tracked and the energy from the occupants can be estimated.

Estimating the metabolic rate of each person in the building has a total systematic uncertainty of around 30% [81]. This high uncertainty is mostly due to the high range of metabolic heat rates in building occupants, especially since factors such as height, weight, age, and gender are not being taken into account. Each optical turnstile must be positioned above the doorway and there should be no obstructions between the door and the floor so that each occupant entering and leaving the building. The uncertainty in the tracking of the occupants themselves is around 5%.

The webcam is installed above each entrance to the building and two reflective strips are installed on the ground below the webcam. The image from the webcam is sent to a computer that is running the image processing software. The software was developed by an undergraduate capstone group at McMaster. The software is able to determine the direction of the heat signature by measuring which line is broken first; this updates a counter that keeps track of the number of occupants in the building[50].

The proposed system does not measure energy so the heat gains from occupants must be estimated. Most commercial or institutional buildings have a significant number of occupants that are either walking slowly or working lightly while seated. This is an average gain of about 125W/person [82]. If different sections of the building are expected to have occupants doing more strenuous tasks, such as a gym or a machine shop, the sensors should be set so that the occupancy is tracked in the different zones. The estimated metabolic heat rate should be selected for each space depending on the usage. This allows for a more reasonable estimate to be made for occupancy heat gain in each specific area of the building.

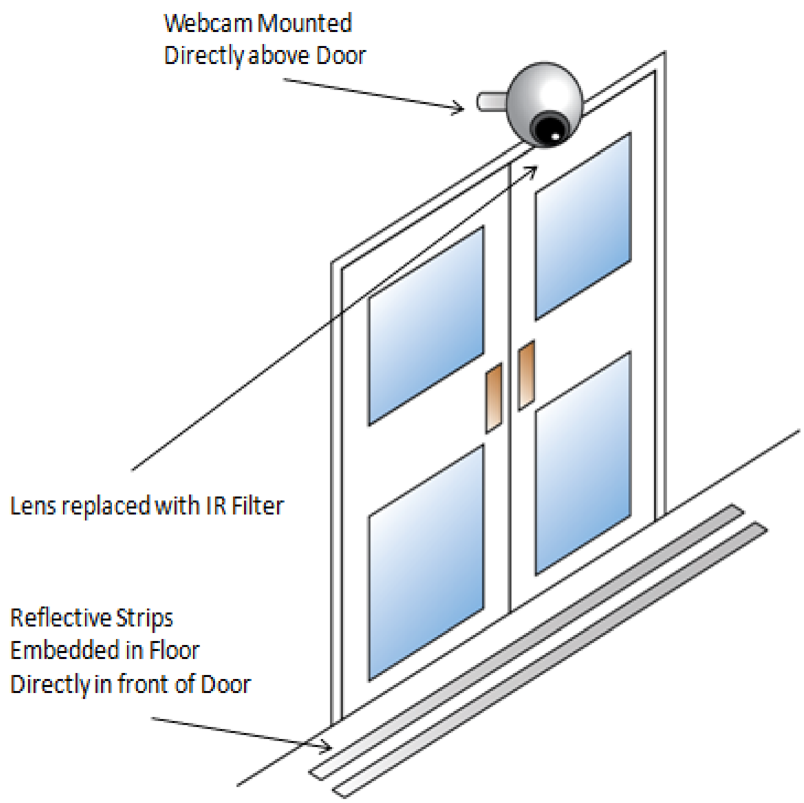

Figure 18: Diagram for Installation of the Occupancy Tracking System

Infiltration

In a smaller building, a blower door test can be used to measure the infiltration rate. However, due to the large volume of commercial buildings, to adequately measure infiltration is a tracer gas test. A tracer gas test releases a known quantity of a specific gas into the zone and a receiver measures the concentration. The concentration of gas in the zone then correlates to the leakiness of the room, and an estimate of the air changes per hour of the zone can be determined.

To achieve the most accurate system the type of tracer gas test that should be run is the constant concentration method. In this method the gas injection system attempts to maintain the concentration of the gas at a target concentration, C_T. When using this control technique, there is little accumulation of the gas within the zone and as a result the uncertainty in the measurement over an extended period of time is much lower [83]. This allows for longer measurement periods, on the scale of days, which gives the possibility to determine different correlations that are dependent on the weather. To ensure that the system is only measuring leakiness of the building it is important to ensure that the leakiness of the zone is only due to exterior walls. To ensure this, the ventilation system to that zone must be shut off and the interior doors should be sealed as well as possible. The zone should remain undisturbed during this time. Because of this, the test should take place before the building is occupied. During this time, the exterior conditions should be monitored to determine if the outside conditions affect the infiltration. Once the test has been completed, the correlations for wind speed and infiltration can be made, this allows for an estimate to be made for the building infiltration throughout the year without the invasiveness of the tracer gas test.

Infiltration can be broken down into two separate parts, air changes through open windows and doors, and air changes due to the leakiness of the building. As discussed in Chapter 2, there is also a correlation between door and window opening and infiltration rates. As such, part of the infiltration losses can be estimated by knowing when a door or window is open and the area of the opening as well as the pressure difference. To accurately determine when the door is open proximity sensors will be used. Each entrance to the building will have a proximity sensor installed on the door and the door frame. The sensor in the door frame should be set up to send a signal when the door is open. This raw data can then be turned into an estimated infiltration value based on the empirical correlations. To estimate the pressure difference a pressure sensor should be on the inside of the building in the different zones. The outside pressure may also come from a pressure sensor or a reliable weather station in the area.

Wind Speed

In order to correctly correlate the infiltration rates as discussed in Chapter 2, it is important to understand the pressure around the building. As shown earlier, measuring the wind speed around the faces of a building is an important. Measuring the wind speed around a building may also help to understand correlations between the weather and the conduction heat transfer. While the installation manual recommends being sufficiently away from any obstruction this is not relevant for these wind speed measurements. The installation guide for the sensor is assuming that the user desires the free stream wind speed for weather purposes and is attempting to mitigate changes in wind speed due to the presence of obstructions.

The fact that obstructions can change the free flow wind stream is irrelevant when using these sensors in this application. This is because this application specifically wants the wind speed at the wall, not the free stream wind velocity. If the free stream wind speed is desired many cities have a weather station that can give this information, the local wind velocity is much more important than the bulk flow in this application.

To get a more accurate idea of the local wind velocity on each face the wind velocity sensors should be located at various positions around the building. Sharples completed a similar measurement when measuring wind speed around an 18-storey building [84]. They utilized one wind speed sensor for every 6 stories. The wind speeds were measured one meter from the building. For this study, it is recommended to use one sensor for each exterior face of the building. There should be a minimum of one sensor per face as per Sharples. The sensors should be installed in the middle of the face and can be assumed to be representative of the rest of the area for that side. The sensors should be installed on a pole attached to the building at least 1 meter long to adequately capture the wind speed and the wires run from the pole into the building. The sensor should be capable of determining the direction of wind as well.

Electric Loads

The bulk of the electric loads should be measured with a feed-through meter. They are required to be installed in the utility room, away from the actual load. These meters should be installed on all electric loads used throughout the building to ensure that the total electricity consumption is being measured. This information can also be used to estimate the heat load from electric sources as all electrical energy is eventually converted to thermal energy in the building..

Bulk CO_2 Levels, Relative Humidity and Zone Temperature

A combination carbon dioxide (CO_2), relative humidity (RH) and temperature sensor is a common sensing device for building control systems. These combined sensing systems should be placed in each zone to control occupant comfort within the building. When they are installed they should be on a wall away from the door and away from the air supply or return, to ensure that the air is well mixed and the temperature is representative of the room as a whole.

Calibration of Sensors

It is also important to keep the sensors calibrated in order to maintain their accuracy. Instructions for calibration for each sensor have been given in Appendix C.

4.4 Uncertainty Analysis

The uncertainty analysis for this project was completed using a Type-B Monte Carlo simulation at the peak heating condition. A Monte Carlo simulation uses the probability distribution of the uncertainty of the sensor when it is measuring the actual value in the building. While the temperature of the room may be 23 ^{o}C, due to uncertainty in the sensor it may read any number of values between 22 ^{o}C and 24 ^{o}C. As the probability distribution for sensors is a normal distribution, the values closest to the actual value are more likely. For the Monte Carlo analysis, every variable that will be measured must be accounted for, and all of the uncertainty must be combined. When measuring heat transfer from advection there is a constant for heat capacity and three variables, one for mass flow, and two to calculate the temperature difference. Values for the three variables are randomly generated to model what will be the expected readings from the sensors. This generates a value for the amount of heat transferred. This process is completed many times for every energy flow within the building. This generates a normal distribution of the expected values when measuring the building energy. Two times the standard deviation of the distribution can then be used to determine the uncertainty of the sensor array to 95% confidence [85].

In order for the uncertainty analysis to be as conservative as possible the condition with the largest energy flows was used. When comparing peak heating and cooling energy from the energy balance it was determined that the energy flows were significantly higher at peak heating. Thus, using energy flows at peak heating will represent the largest uncertainty in the system.

The analysis was completed using Microsoft Excel and the XLSim add-on. In Excel, a representative model was created at the peak heating condition to simulate each type of sensor, number and the total uncertainty in each measurement. XLSim utilizes the random number generator function in Excel to simulate multiple iterations at the peak heating condition. Each iteration is collected and over multiple iterations a normal distribution can be created that will determine the total uncertainty of the sensor array.

The equations used in this uncertainty analysis were discussed in Chapter 2. These equations were:

Advection Heat Transfer

$$Q = \dot{m} c_p \Delta T \tag{24}$$

Where $\dot{m}$ is the mass flow of the fluid, c_p is the heat capacity and ΔT is the temperature difference between the hotter temperature and the colder temperature.

Heat Exchanger Equation

$$Q = UA\Delta T_{LM} \tag{25}$$

Where U is the heat transfer coefficient, which is dependent on the design of the heat exchanger, A is the heat transfer area, also dependent on the specific design of the heat exchanger and T_{LM} is the log-mean temperature difference[21]. From these two equations it can be determined that the entire sensible heat load from the HVAC system is dependent on the temperature difference and sometimes the mass flow of the fluid. By measuring the mass flow and temperature of the fluid throughout the building, the values for $Q_{Generated}$, Q_{Stored}, and $Q_{Ventilation}$ can be determined.

Conduction Heat Transfer

This equation has changed from the literature review as conduction will be measured directly. The new equation that was used in the uncertainty analysis is:

$$Q = \sum q_{cond,wall} + \sum q_{cond,window} \quad (26)$$

Infiltration Heat Transfer

The infiltration equation has also changed, as a test will be completed during the commissioning phase, before building occupancy, the measured energy flow will be dependent on that original measurement.

$$Q = \dot{q}(P,v)\rho c_p \Delta T \quad (27)$$

Where $\dot{q}(P,v)$ is the original flow of air in m^3/s scaled by pressure and wind velocity as detailed before, ΔT is the difference between the inside air temperature and outside air temperature, ρ is the density of air and c_p is the specific heat of air. The air flow measurement for infiltration is dependent on the pressure difference between the indoors and outdoors, which is dependent on many factors. The different factors that affect pressure are the stack pressure, wind pressure and the general leakiness of the building. The total effect of all of these parameters can be defined by the equation [22]:

$$\Delta p = s^2 C_p P_u + HP_T + \Delta p_I \quad (28)$$

Δp can be directly measured with pressure sensors on the interior and exterior of the building. This can then be correlated to the infiltration coefficient determined in the commissioning stage of the building.

The equation is the same for infiltration through open doors, however it is also dependent on the time the door is open.

$$Q = \dot{q}(P,v)\rho c_p \Delta T \cdot t \quad (32)$$

Solar Heat Gain

$$Q_{solar} = A_w \times T \times S \tag{33}$$

Where Q_{solar} is the average solar gain in watts; A_w is the area of the opening in m²; T is the fraction of incident radiation transmitted to the interior; and S is the solar flux on the surface in W/m² and is measured by the pyranometer [23].

Occupant Heat Gain

Building occupants are a large source of thermal energy in a given space due to the metabolic rate of each person within the zone. The governing equation for the energy added by the occupants is given by:

$$Q_{Occupant} = \sum_{r=i}^{n} q_i \tag{34}$$

Where n is the number of people in the building and q_i is the individual metabolic rate of each person.

Electric Load Heat Gain

Finally, the electrical energy loads also affect the thermal energy loads in the building. The thermal energy is dependent on the electrical energy consumed by each individual piece of electrical equipment and the individual efficiencies of that equipment. As a result, while the total electrical consumption can be measured using an aggregate meter, the building must be sub metered in a zonal approach level to ensure that a better estimate can be determined for the thermal energy balance.

In order to complete the error analysis it is required to put the equation in a spreadsheet that is used to complete the building energy balance [85]. It is also required to have a mean value and a distribution of this mean value. The shape of the distribution must also be known. It is best practice to assume a normal distribution for the errors associated with the sensor as well as any systematic error of the sensor due to the installation. A rectangular distribution is assumed for the error associated with the resolution. The spread of a set of values, and therefore its shape, is dependent on the probability. For any random error it is more likely that the values occur near the mean value, with less probability of occurring as you move away from the mean value. This causes the shape of random uncertainty to be a normal distribution. Errors associated with span are not random in nature. If a sensor has a span of 0.1 it is equally likely for the actual value to land anywhere in that range of 0.1. As these values are equally likely they have a rectangular distribution. It is highly unlikely for any other probability shape to occur [86]. The uncertainties in a Monte Carlo error analysis must be given to one standard deviation. Uncertainties are usually quoted to two standard deviations. For a normal distribution to convert to one standard deviation the value is divided by two. For a rectangular distribution the value must be divided by the square root of two [86].

The mean values used in the uncertainty analysis were given from the energy model at the peak heating condition. When multiple sensors are required to get a total value, the total value measured in the model was divided by the number of sensors. Temperatures and flow rates are determined from both the energy model and the standard that was used to create the energy model, such as ASHRAE 90.1. As these values are generally industry standards. It is best to use the values from the energy model, but in lieu of these values being available the standard values should be sued in their stead. The mean values should all come from the peak heating or cooling scenario, depending on which scenario has the higher mean values of energy flows. Many loads in a building will always be inserting heat into the building or removing heat. Occupancy gain, solar gain, and electrical gain are always putting heat into the building. Occupancy gain and solar gain are the sensors with the highest uncertainty. The other energy flows all depend on temperature difference between the inside and outside of the building. In Canada, the difference between the outside temperature and the inside temperature is significantly larger in the winter than it is in the summer. Because the energy flows are larger, there is an increased amount of uncertainty when compared to peak cooling.

The distribution of the mean values was determined by combining different sources of uncertainty for each measurement. There is uncertainty in the measurement of each sensor, uncertainty in the resolution of each sensor and systematic uncertainty from installation and different assumptions used in the sensor array. For heat flux transducers, there was an uncertainty from the systematic error as defined by Flanders, an uncertainty in the reading itself as defined by the manufacturer, and an uncertainty from the span as defined by the manufacturer. At the peak condition of 7 W/m^2 of conduction, these values were 6%, 0.25 W/m^2 and 0.1 W/m^2. The values given from the manufacturer can be assumed to be at 95% confidence, or two standard deviations. This must be converted to one standard deviation as described above in this section. This gave uncertainties of 0.21 W/m^2, 0.125 W/m^2 and 0.0577 W/m^2.

For this reason the uncertainty was accounted for through other sources. The systematic error determined in the installation section was added in quadrature to the uncertainty given in the material data sheets. This gave the total uncertainty for the sensor. As there are also simplifying assumptions in this energy monitoring system, the amount of uncertainty was estimated and was added in quadrature to the sensor uncertainty to give the total measurement uncertainty. For conduction that would be:

$$E = \sqrt{0.21^2 + 0.125^2 + 0.0577^2}$$

$$E = 1.48\, W/m^2$$

When an average value was required for the simulation, such as in the case of conduction, the point value was estimated to be representative over the entire applicable surface. It is also important to ensure that the number of sensors is being accurately represented in the spreadsheet. For example, a number of sensors are required to measure the total conduction through the envelope. For this reason, if only the total conduction is used in the uncertainty analysis, the total uncertainty will be underestimated. It is better to split the conduction measurement over the total number of predicted sensors to more accurately represent the real-life system.

The resultant error analysis is a conservative estimate of the uncertainty of the sensor array. It is possible that once the array has been installed the direct measurements of the sensor array can be used. This will allow for a Type-A error analysis to be completed.

Chapter 5: Case Study of Hatch Centre

As mentioned in the introduction, this energy monitoring system is will be implemented in a building on the campus of McMaster University. This Chapter will go through the methodology outlined in the last three Chapters and will apply it to this new building project.

5.1 Applied Energy Model

As recommended, the energy model was completed with the UI for OpenStudio and SketchUp using the EnergyPlus engine. At the time of the creation of the energy model the building exterior had been finalized and some of the building systems, including the HVAC system had been determined. This caused a mixture of information to be used to complete the energy model. The building is a 3-storey building connected to an already existing building on one side, the John Hodgins Engineering Building (JHE). There is a small basement area for a small electrical room.

The exterior of the building was given in architectural drawings. A composite 3-D model was created using these drawings as a reference using SketchUp. The model can be observed below in Figure 19 and details are provided in Appendix A.

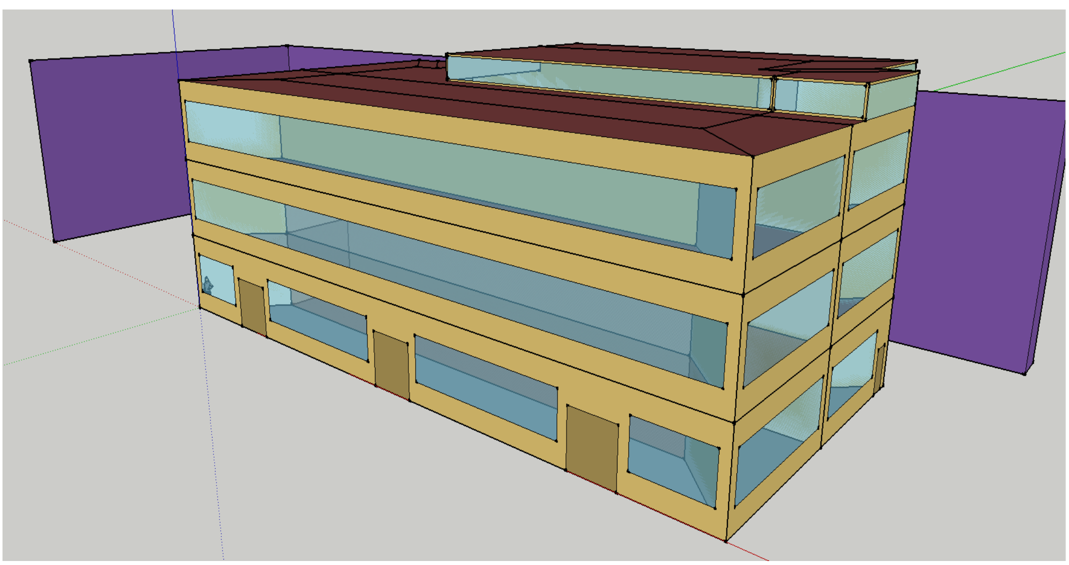

Figure 19: 3-D Energy Model of the Hatch Centre Completed with SketchUp

As can be observed in the figure, JHE has been represented in purple. The building was assumed to be directly adjacent to JHE on the north side of the building, where the Hatch Centre would use the exterior wall of JHE for its north wall. It was assumed that there would be a machine shop in the south side of the building in floors 1 and 2, with an opening in between the two floors. The machine shop was on a different HVAC system to account for the increased flow rate required to go to the space. All of the heating and cooling loads would come from the campus heating and cooling system, that uses steam for heating and chilled water for cooling. Each individual zone had a variable air volume (VAV) system with a re-heat coil. The air handling units were assumed to be 100% outside air with a variable frequency drive to change the flow rate of the supply air. The model has 50% window to wall ratio as defined by the project specifications at that point. To simulate the lack of conduction through the wall adjacent to JHE, the surfaces along that side have been defined as adiabatic. All material and scheduling assumptions can be found in Appendix A.

All other information had yet to be determined, as such, it was assumed that the building would be up to the ASHRAE 90.1 energy code and all values were used in conjunction with this energy standard.

5.2 Energy Model Results

The completion of the energy model will aid the energy monitoring system in three ways: it qualitatively determines if there is a systematic spatial distribution due to the building orientation and its surroundings, which aids in the selection of locations for the sensors. It quantitatively determines which loads are the largest causes of the heating and cooling loads throughout the building, which helps to ensure that all energy flows have been accounted for and gives information on which sensors are required. The results can be used to determine the ranges of energy flows within the building, which are useful when selecting sensors and the results can be used for inputs into the uncertainty analysis for the sensors.

The energy model is important in that it affects the other four steps in the process of developing this sensor array. It must be remembered that a shoebox model may not use the exact HVAC systems and building materials as the actual building. As such the results from the energy model are used to shift the focus to more important areas, such as which sensors are the most important for the final design and which sensors should have the lowest amount of uncertainty. However, in the uncertainty analysis there is no other information available on the energy flows as there is no data on the building before it has been built. As such, the results from the energy model should be used with confidence in that step of the process.

<u>Spatial Distribution</u>

A spatial distribution of energy is defined as changes in energy flows along the face of the building vertically, along a face of the building horizontally, or when the orientation of the building face changes. It is important to know where a spatial distribution may occur because it can help to determine when a point measurement can be seen as representative of a larger area. If an energy flow has no spatial distribution on the same floor, then one measurement can be taken per floor and that value can be assumed to be representative of the other point on the same elevation, while this may modestly increase the measurement uncertainty, this will reduce the cost of the sensor array.

Not all of the energy flows have the potential for a spatial distribution. For example, the infiltration through the walls may change depending on the wind on the face of the building, but the thermal energy from lighting will remain constant. In addition to this, some of these flows would change the design of the energy monitoring system. For example, there may be more people in one area of the building but due to the way occupancy will be measured this will not affect any design decisions. Energy flows that meet both criteria of having a spatial distribution and can affect the design of the sensor array include infiltration, conduction and solar gain. For solar gain, it is apparent that any shading on the building may affect the amount of direct solar energy incident on the building. The energy model can take this into account when the source of shading is known, however, at the beginning of the design phase, the specific location of trees may not be understood. This limits the amount of information that can be taken from the energy model and must be taken into account during the analysis.

In order to effectively measure the spatial distribution the original energy model discussed in Section 3.2 must be modified to improve the granularity of measurements. As seen in Figure 6, there is one large zone on the south side of the building. These large zones must be split into many smaller sections along the exterior faces. Without making this change to the base model, it would be impossible to tell if moving horizontally at the same elevation would cause a change in energy flow. By observing the difference in values between floors and between these smaller zones it can be determined where a spatial distribution may occur. A plan can then be formulated to help the sensor array take this information into account to maintain the level of uncertainty while minimizing the number of sensors.

Once the new energy model has been completed, the conduction, infiltration and solar gain energy flows need to be observed in key areas. The analysis should look at a zone facing the same direction on a different floor, on the same floor facing the same direction, and on the same floor facing different directions. These zones may have different areas, so the energy flows should be normalized per area. If possible, normalize the energy flows for both window area and wall area and note where the wall material may be different in the building energy model.

The spatial distribution analysis is completed by looking at different zones that are spatially different, either horizontally, vertically or directionally. The first energy flow looked at will be solar heat gain. It can be observed from Figures 6-9 that when the energy flows are normalized to the surface area of the window in the zone, there is no dependence on the vertical or horizontal position of the zone in the building. However, there is a dependency of the orientation of the surface on energy flows.

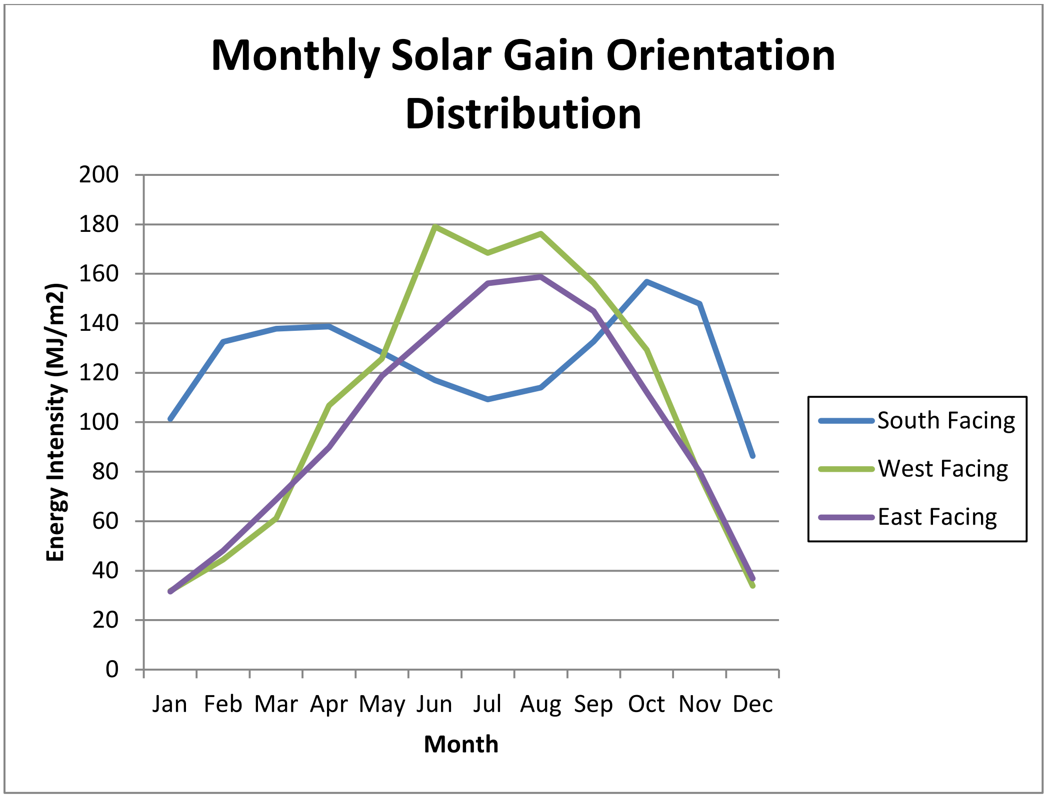

Figure 20: Average Monthly Solar Gain for Building Faces of Different Orientation on the Third Floor of the Building Model

Figure 20 shows there is a difference in solar gain when comparing the south, west and east faces of the building. This is to be expected as solar gain is dependent on the angle of the sun in the sky. This angle varies throughout the year due to the Earth rotating around the sun. The angle also varies throughout the day due to the Earth rotating about its axis. In the summer the sun is higher in the sky while the sun is on the south side of the building, causing a decrease in solar gain on the south side. On the east and west faces in the summer, the sunlight has less atmosphere to travel through, increasing the intensity of the solar radiation that will shine on the building. The solar gain is also dependent on the weather, so in January and February when there is more snow in the Hamilton area the south side of the building sees less solar gain.

For the building energy monitoring system there are two conclusions that can be made from this comparison. The first conclusion is that when measuring solar gain, the measuring device should be placed or covered in such a way that it is only measuring solar energy from one cardinal direction. If the measuring devices receive sunlight from multiple directions, the amount of solar radiation entering the zone would be overstated. This error could be compounded if a pyranometer was used to estimate the solar energy for multiple zones. The second conclusion is that there must be at least 4 measuring devices in the building, one for each direction the building will be pointing. There must also be a measurement to account for the shading on the building, as if a window is being shaded, it will have less solar energy entering it. As the specific location of trees was unknown at this point in time, the only shading on the building in the energy model was from surrounding buildings. If trees or other obstructions were used on the building, these would need to be accounted for. By utilizing a shading measurement and accounting for the locations of shade on the building faces, a single pyranometer would be able to accurately estimate the amount of solar energy entering each exterior zone on the same face.

As shown in Figure 21 and Figure 22 it is apparent that the model is predicting no distribution in solar energy moving horizontally or vertically throughout a building face. This is not an expected result as real-life experience shows that surrounding obstructions may cause shade on the surfaces unevenly. This would ultimately change the solar gain entering the building. This result can be attributed to the shortcomings of the building energy model and the lack of knowledge found at the beginning of the building design phase. The model assumes an even solar distribution on each face. This result can be rectified in the future with a study of potential shade sources being completed on the building site. For this research that would be difficult, as there are currently trees on the building site that are likely to be removed during the construction process.

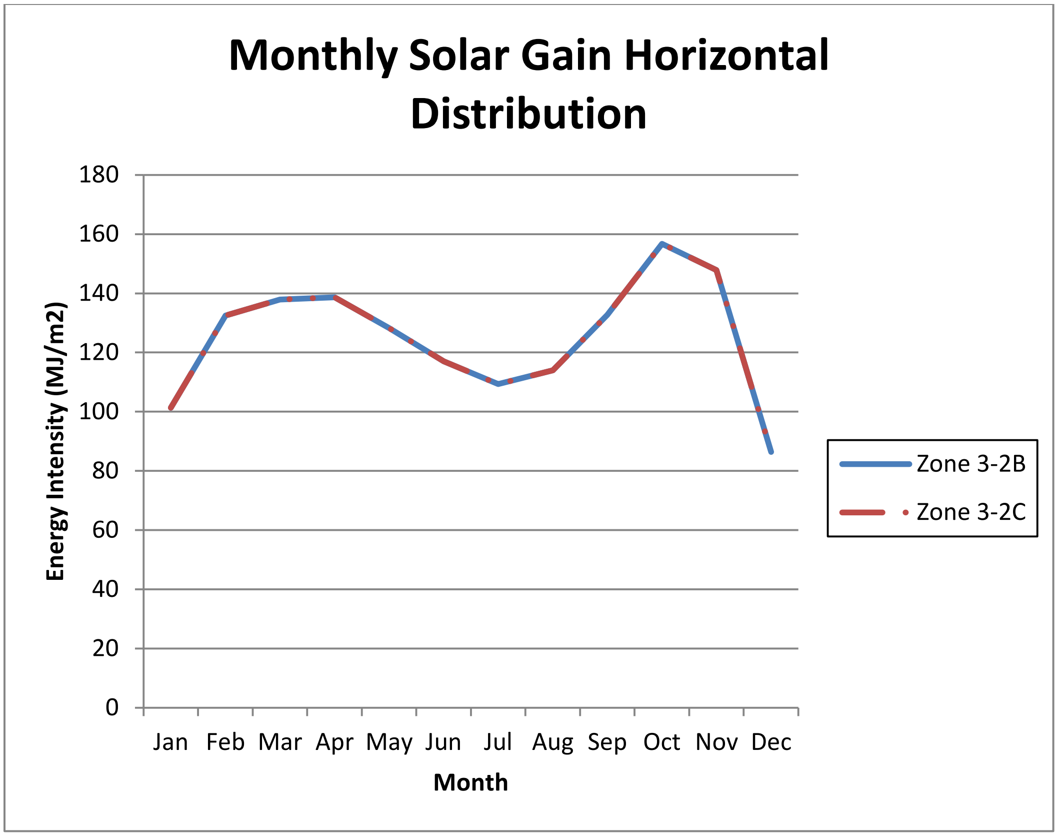

Figure 21: Average Monthly Solar Gain for Building Faces of Different Horizontal Position on the South Face of the Building Model

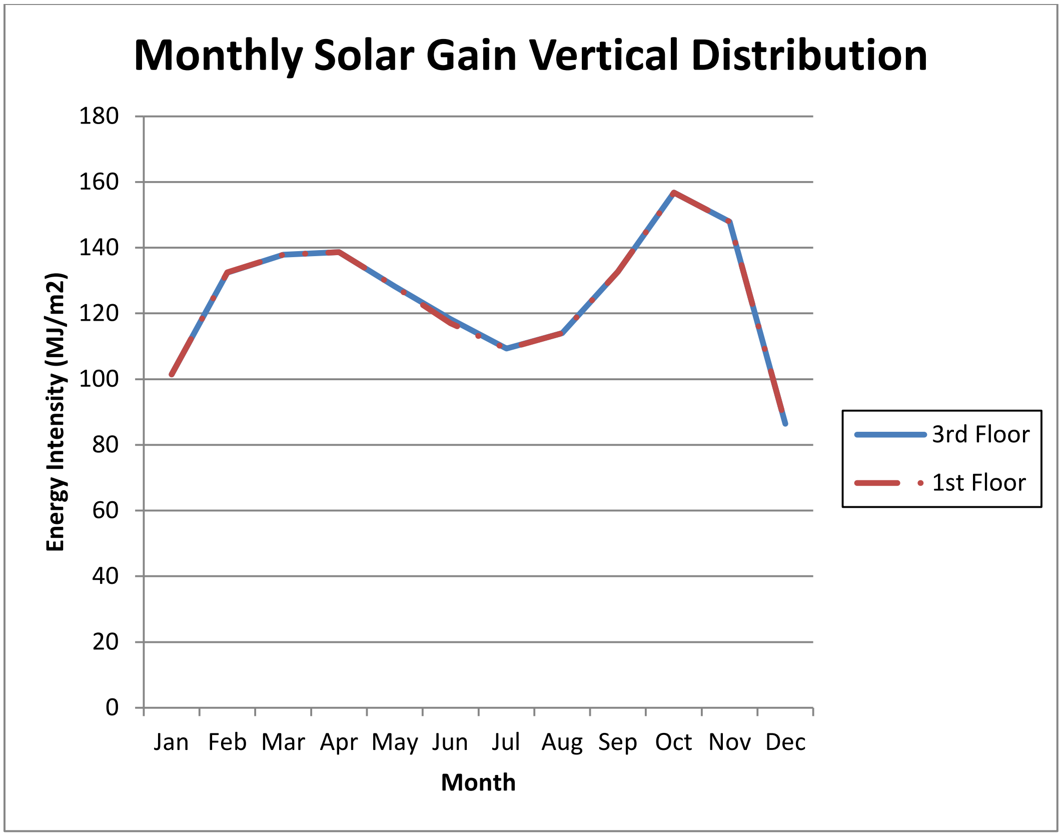

Figure 22: Average Monthly Solar Gain for Building Faces of Vertical Position on the South Side of the Building Model

Even though there are known shortcomings in the model, there are still conclusions that can be made from these comparisons. First of all, because of these results it can be determined that solar energy does not need to be measured on each floor; a minimum of one solar-energy measuring device for each cardinal direction is adequate. Furthermore, while shading can unevenly be applied to the surface of a building, this model shows that neglecting other effects, there is no discernible difference in the potential solar gain entering through surfaces that are facing the same direction. From this it can be concluded that if there is a way to measure the location of shading on the building surface it is possible to accurately measure the solar heat gain entering through the building envelope. In essence, to accurately measure the solar gain in a building there must be at least one unshaded pyranometer and one shaded pyranometer for each direction the building is facing. There must also be a system that determines which areas of the building are under shading as well as which of those areas allow light into the building. By taking advantage of this conclusion, the cost effectiveness of the entire system can be improved, while maintaining the total system accuracy.

The analysis described in the previous paragraphs was also completed for measuring conduction through the exterior surfaces of the building, the results of this analysis can be observed in the figures below. The same trends observed in solar heat gain can be observed here as well, where there is no discernible difference in conduction through the walls and windows for surfaces that are facing the same direction. The one exception to this can be observed on the south side between floors 2 and 3 due differences in the HVAC systems in the building energy model. The south side of the building on floors 1 and 2 in this energy model is the location of a machine shop, due to the presence of fumes associated with a machine shop, the ventilation in this area is higher, this would allow for more energy to leave the building in this area. The building is designed in such a way to allow for mass transfer of air to move freely between floor 1 and 2 in the machine shop area. As there is a different HVAC system, and there is free mass transfer between the two floors it is possible that the temperature may differ from the setpoint more in this area, causing more conduction to occur.

Figure 23 shows that average conduction is dependent on building orientation; this is expected as different orientations have different solar gains and different internal temperatures. Both of these factors will affect the temperature difference between the outside surface and the inside surface, altering the conduction. The graph shows energy intensity in MJ/m^2. This was calculated by taking the average conduction through the wall, which was an output of the energy model, and dividing by the area of the wall.

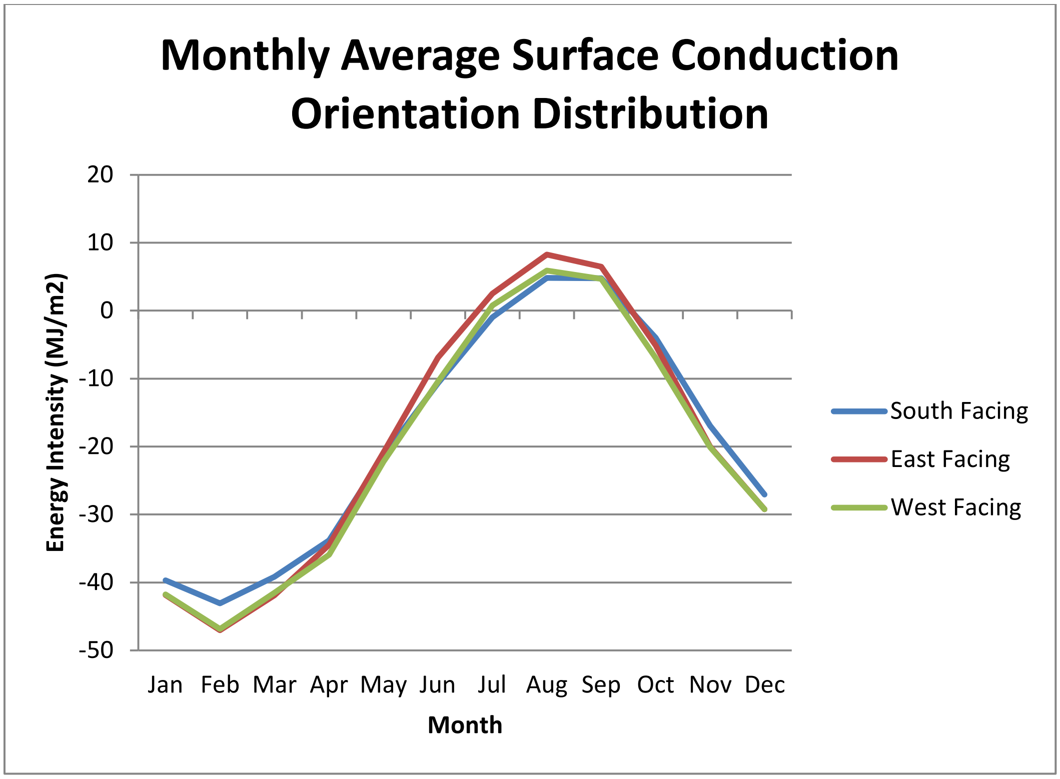

Figure 23: Average Monthly Conduction for Opaque Building Surfaces of Different Orientation on the Third Floor of the Building Model

Figure 24 shows that there is no dependency on horizontal position for conduction, but Figure 25 shows that there may be one for vertical position. Based on what has been observed during the solar gain and conduction analysis of the energy model, it does not make sense for conduction to be dependent on vertical position. The apparent dependency on vertical position can be attributed to one of two things. In the energy model, to mirror what is expected in the regular building, the second floor south side zone is a part of an HVAC system that is independent from the one used on the third floor. Also, the second floor zone does not have an opaque floor but what is called an air floor. This is a construct used in the model to allow light through to the first floor zone, again an attempt to mirror the current design of the building. Either of these effects could cause a change in conduction affecting the results. In order to make sure that the model is working correctly the same analysis will be done to the east side as seen in Figure 26

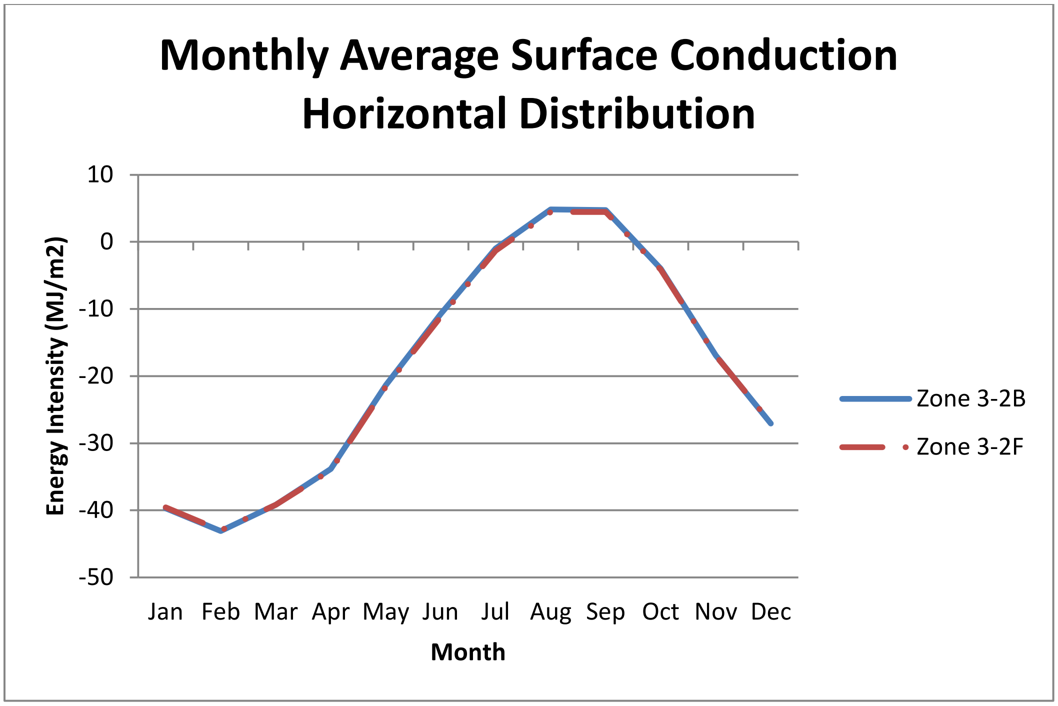

Figure 24: Average Monthly Conduction for Opaque Building Surfaces of Horizontal Locations on the Third Floor of the Building Model

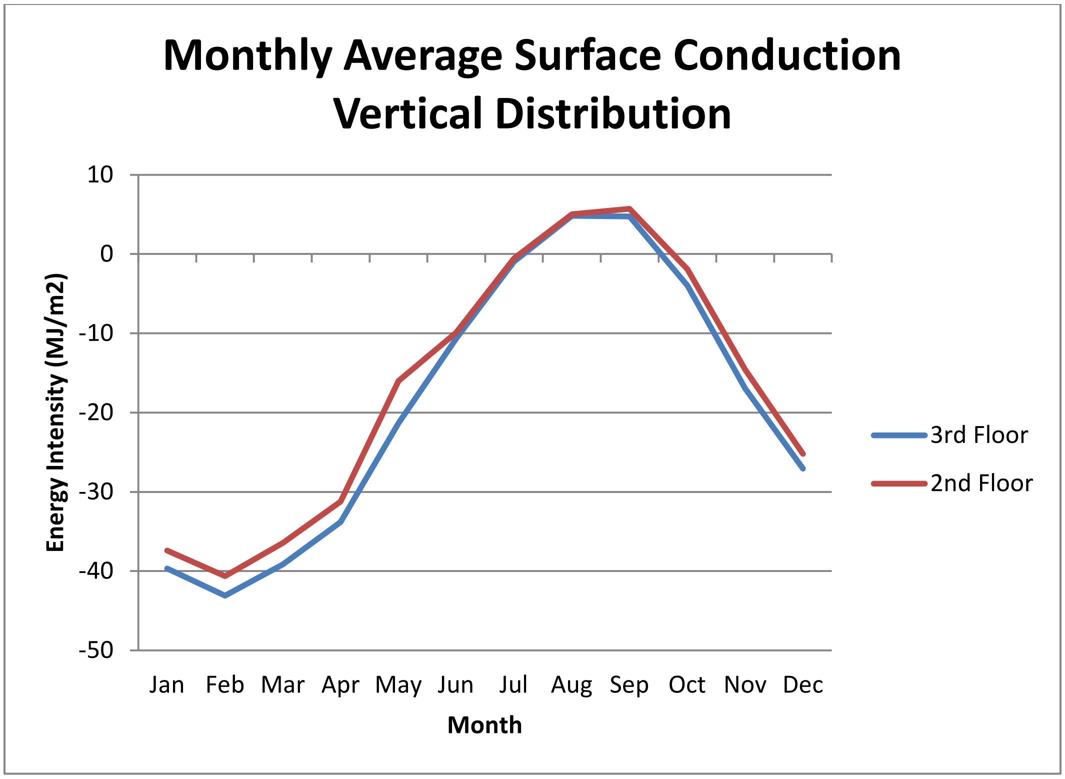

Figure 25: Average Monthly Conduction for Opaque Building Surfaces of Vertical Position on the South Side of the Building Model

Figure 12 shows a more expected result from the energy model, as it assumes constant conditions of temperature and wind speed on the exterior surfaces. The HVAC system is also the same in these zones which will keep the different zones at the same temperature setpoint. This energy model has also shown near constant conditions in each zone on the same face. However, this assumption is not correct in real-world applications. There are slight variations in interior and exterior conditions in a building. In an operational building, a zone may have more occupancy gains or gains from electrical equipment, there may also be differences in the solar heat gain. These would all change the interior surface temperature. On the exterior surface, the local wind effects may be different; the surface may also be partially shaded. These would affect the outside surface temperature. In practice, these effects may cause small differences in the ΔT, which would affect the conduction rate. It can be seen that conduction through the surfaces is a small factor in the building energy balance at around 10%. This exact value is dependent on building design and can be increased if a material with a smaller R-value is used. The effect on the energy balance calculation would be minor enough that a small amount of heat flux transducers can be used. The specific effects on the design decisions will be discussed in Chapter 5.

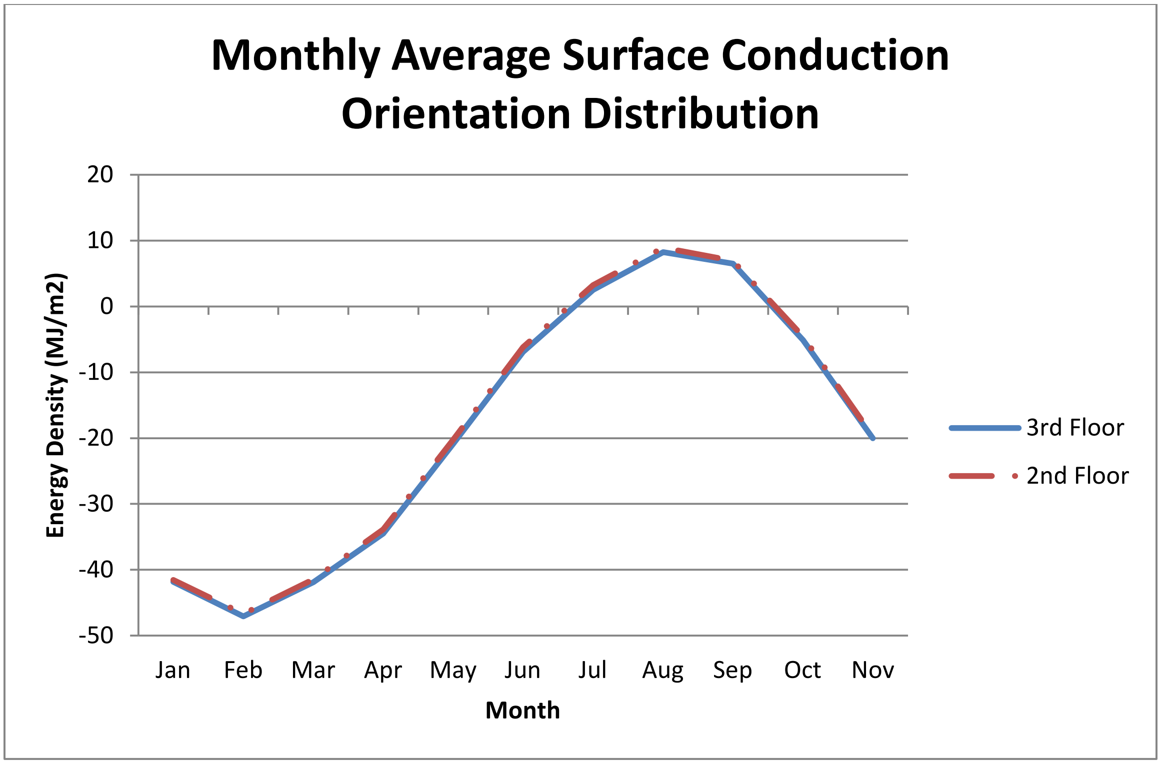

Figure 26: Average Monthly Conduction for Opaque Building Surfaces of Vertical Position on the East Side of the Building Model

As in the solar heat gain analysis, the limitations of the energy model do not disqualify qualitative conclusions from being drawn. Using the results from Figure 25 and Figure 26 it can be seen that when there are variations in the interior and exterior conditions in each zone, the conduction through the envelope will change. This proves that at least one device for measuring conduction must be used in each zone to accurately measure the conduction gains or losses. There must also be a conduction sensor for each surface type in a zone, such as a wall or a window. In this section, the shortcomings of the model were discussed, and while the differences are projected to be small, it is important to determine what effect this may have on the building. As such, more research must be completed before any final conclusions. Other factors that affect the design of conduction measurement will be discussed in Chapter 4.

Finally, the infiltration results from the energy model were analyzed infiltration was equal throughout the external zones when normalized by zone volume, as can be seen in Figure 27. This result is representative of the results seen when looking at horizontal distributions and vertical distributions.

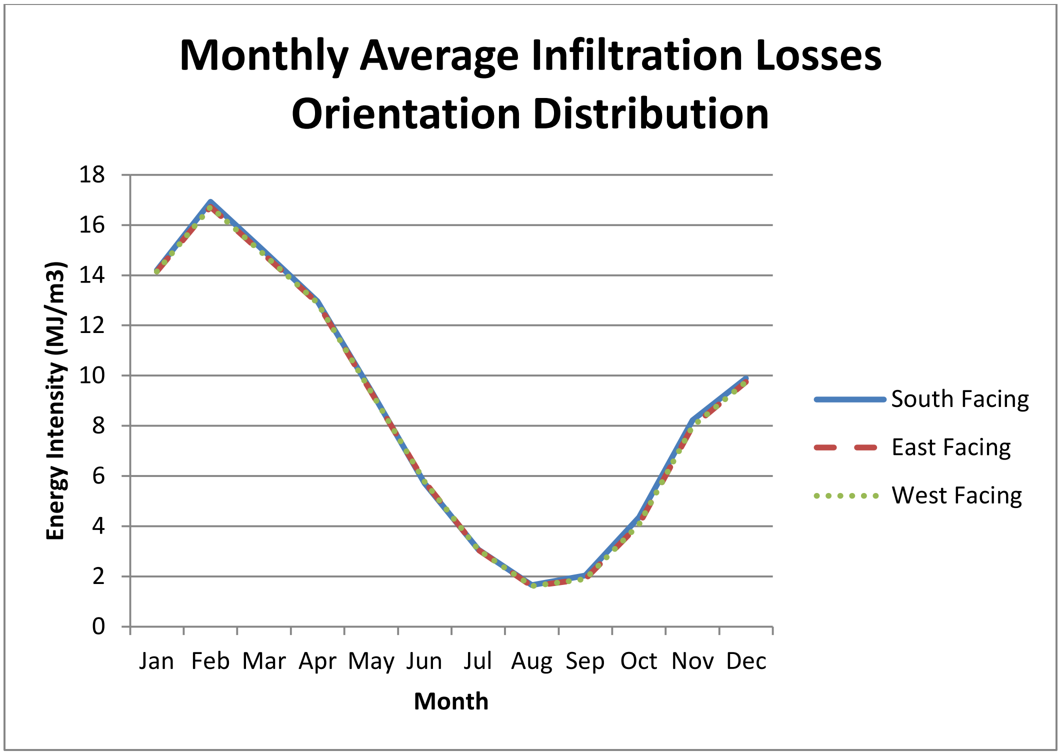

Figure 27: Average Monthly Infiltration Losses for Zones of Different Orientation on the Third Floor of the Building Model

While this distribution is not expected in a real building, this occurs in the building energy model due to how infiltration was calculated. In the model there are three ways to calculate infiltration, constant infiltration, a linear relationship with wind speed and a quadratic relationship with wind speed. The constants for the linear and quadratic relationship must be defined by the user and typically these values are not known but can be obtained through different tests once the building has been completed. As the building is not yet completed at the writing of this report, the constant values of infiltration a building given from the building design team were assumed. A sensitivity study could be completed using typical values for the three methods of measuring infiltration. This would help to give an idea of the ranges of infiltration that could be found in the building. However, the constants for wind speed cannot be determined in this phase of the design process but should be completed once the design of the building has been finalized.

In addition to the spatial distribution, the ranges of energy flows in the model and the amount of flows predicted are heavily dependent on the location and parameters of the specific building.

To determine the amount of energy consumed in the heating and cooling months the original model was modified again to help ease the analysis. The thermal zones in the original model were all combined into one zone to facilitate data collection. When the zones were combined, the original heating loads were decreased by 7% and the cooling loads decreased by 6%. This is within the expected values and was deemed a reasonable simplification to the model.

Once the results were obtained from the simulation a problem presented itself, due to the nature of the building energy model and the HVAC system, the building undergoes periods of alternating heating and cooling; as a result, it is hard to separate out which loads impact heating and which impact cooling as it changes from hour to hour. For building energy, months of the year can be separated into heating seasons, where the building is only undergoing heating, cooling seasons, where the building is only undergoing cooling, and shoulder seasons, where the building can be in heating or cooling mode. The shoulder seasons in Canada generally happen during the spring and autumn. In order to simplify the analysis it was assumed that heating and cooling occur separately during the shoulder seasons, even though the contrary was shown in the model, as can be observed below in Figure 28 and Figure 29. While this does increase the uncertainty in the results from the energy model, the analysis would not be possible without this simplification.

Figure 28 shows the breakdown of sensible heating energy by month. The red areas are the months where it has been assumed that only heating occurs in the building. These months include the span of January 1st to May 31st and November 1st to December 31st. These months have 95% of the sensible heating load of the building.

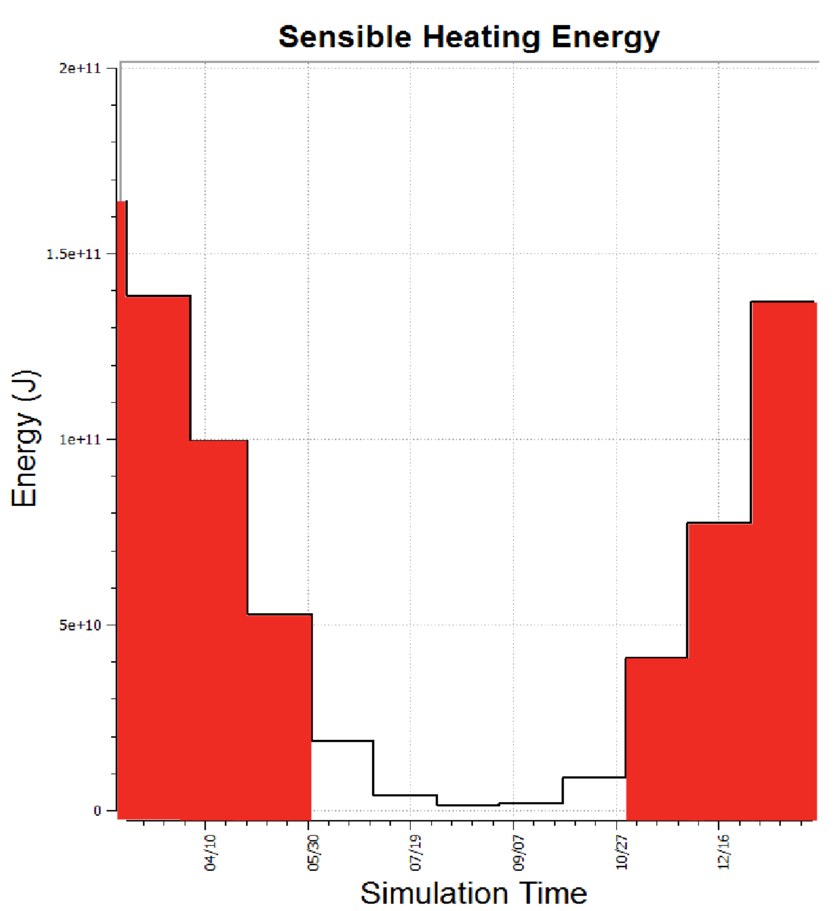

Figure 28: Monthly Sensible Heating Energy for the Building Energy Model

Figure 29 shows the sensible cooling loads of the building, with the red areas the times of the year where it is assumed the building is in cooling mode. The months span from June 1st to October 31st. These months have 70% of the total cooling load. While this is a relatively low percentage of the cooling load, it has already been assumed that the other months of the year only have heating energy. By default, the other months of the year can only contain the cooling loads of the building

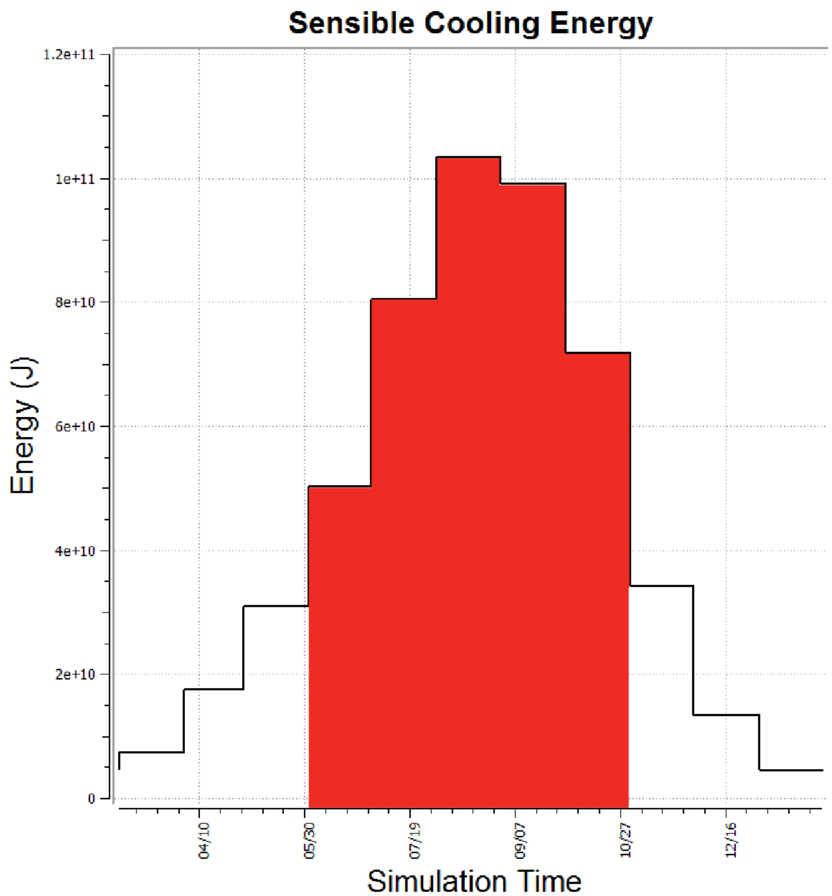

Figure 29: Monthly Sensible Cooling Energy for the Building Energy Model

To complete the analysis of heating and cooling loads, the source of heat energy transfer was accounted for and it was determined whether these energy flows added energy to the building or removed it. In both scenarios, heating and cooling, the difference between the added energy and removed energy was 10%. In the case of heating, there was more energy removed from the building than added, while in the cooling scenario the opposite was true. This is generally expected for a building as it is more likely for a building to be too hot in the summer and too cold in the winter. However, the observed discrepancy is also due to the simplifying assumptions made about when heating and cooling occurs. This was observed due to changes in the total energy consumption in the HVAC system. By combining all the zones into one large zone, it became harder for the HVAC system to keep the system within the temperature set-points. The result is that there was a slight increase in the number of hours where the occupants are uncomfortable in the building due to air temperature being too low or too high. This is a source of error in the energy model, however as the building energy model was not a calibrated model; it is unknown what the effect this will have on the accuracy of the model. As the HVAC system has yet to be designed, it is unknown whether one thermal zone is more accurate than 23 thermal zones, as the original model had. Even though there is this uncertainty, some qualitative conclusions can be made from this analysis.

The resultant energy flow diagrams for both the heating and cooling scenarios can be observed below. On the right of each diagram, there is the amount of thermal energy that went into the building, and through which method. On the right of each diagram there is the amount and method that the thermal energy left the building in order to keep the balance of energy.

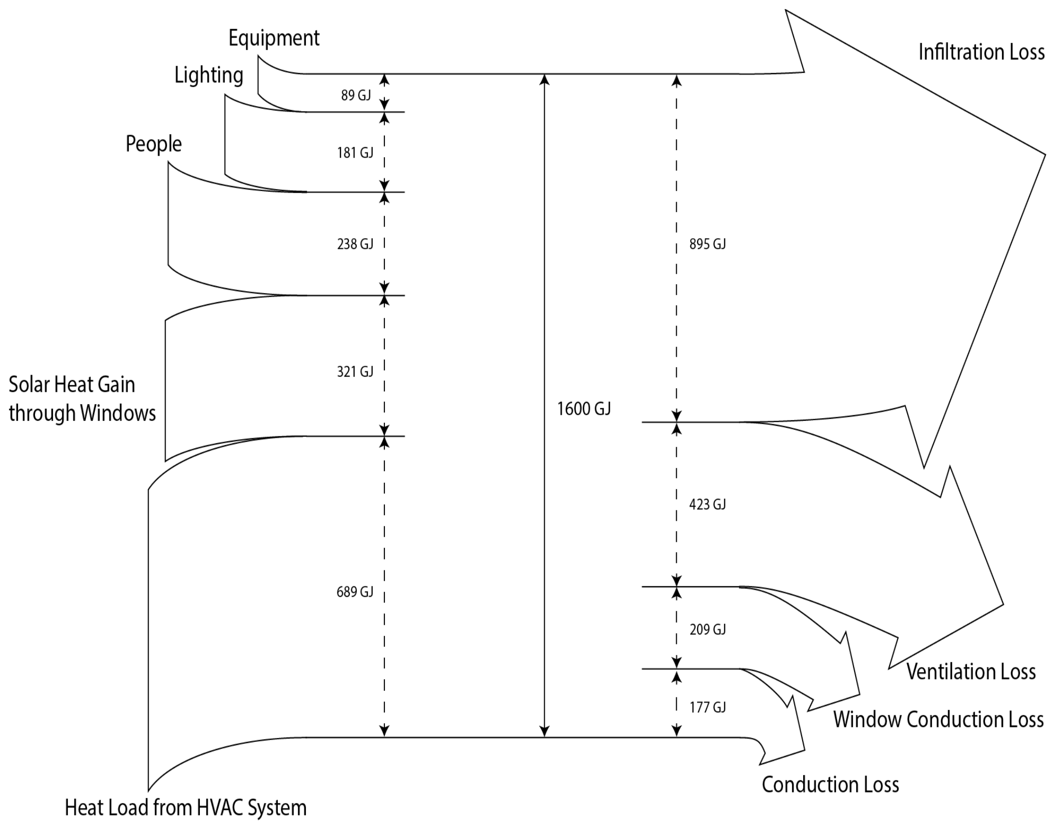

Figure 30: Energy Flow Diagram for the Heating Months during the Building Energy Model

From Figure 30 it can be observed that the largest driver of the sensible heating load in the building is infiltration, conduction losses through the envelope and ventilation losses in the building are the next two largest reasons for heating the building. To help counteract the losses there are solar gain, occupancy, and heat from electrical loads. By observing this diagram, it becomes apparent that measuring infiltration in a building is important in order to complete a full building energy balance. In general, there are few losses that can be ignored, but within conduction the heat loss to the ground was small as were the heat losses through the roof.

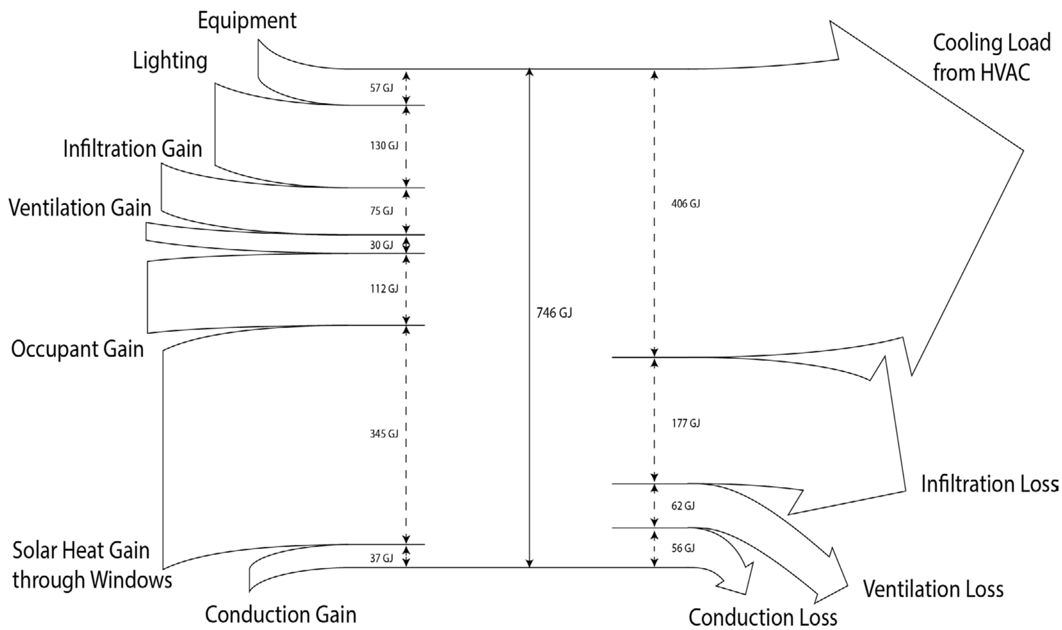

Figure 31: Energy Flow Diagram for the Cooling Months during the Building Energy Model

The energy flows during the cooling months are shown in Figure 30 It can be observed that there are both infiltration gains and losses, conduction gains and losses, and ventilation gains and losses. These occur because in the model the cooling setpoint was set to be room temperature is around 21^{o}C. Looking at the weather data for Hamilton, Ontario there are only two months where the average daily temperature is over 21^{o}C. Because of this, throughout the 5 month period there can be energy leaving the building or entering, depending on the outside conditions.

The energy flow diagrams both show the relative magnitude of the energy flows throughout the building but it does not show the location of these energy flows. The locations of the energy flows were already determined using the zonal energy construct including the building specific parameters. For this building, there are gains and losses from ventilation as well as a few electrical loads. Finally there are the sensible heating and cooling loads that are also building specific parameters. Since conduction heat transfer is so low

The energy model is a useful tool to ensure that each parameter has been accounted for, as well as determining the relative importance of an energy flow for the overall building energy balance. By incorporating the zonal construct with the results of the energy model a clearer picture of the energy flows begins to appear, demonstrating the locations, directions, and relative magnitudes of the energy flows. This information, along with research from secondary sources, is essential to determining the proper installation of the sensors in the energy monitoring system.

As conduction heat transfer is not a significant source of energy transfer throughout the building, there can be fewer sensors used to measure its energy flows with less of an impact on the accuracy. This is helpful as the number of conduction sensors can be reduced, improving the cost effectiveness of the sensor array as a whole. The error associated with conduction heat transfer will increase, but since its energy flows are small it will have a low impact on the error of the system as a whole.

5.3 Energy Balance of the Building

In addition to the zonal energy balance that was discussed in Chapter 3 it is important to discover any building specific features that are required to complete a full energy balance. The next section will discuss specific installation instructions that will ensure these specific building features are taken into account. This building has a few additional features that must be taken into account to ensure that the energy modeling system is accurate.

As there is a machine shop with different air flow requirements, there will be two air handling units on the building. There will also be two separate flows of air being directed to the outside environment. Both of these separate HVAC systems must be monitored.

The occupants in the machine shop will have a higher metabolic rate than the rest of the building due to increased levels of activity. By breaking down the building into more parts, better estimates on occupancy energy gain can be determined

The heating and cooling is also proposed to come from the campus plant. The on campus plant uses steam generation and chilled water loops. A steam monitoring device is required at the point where the steam energy is entering the building.

By creating this checklist of building specific technologies it becomes easier to determine what needs to be added to the zonal construct while ensuring that a complete energy balance is still being measured.

Table 6: Building Specific Parameters for the Hatch Centre

Additional Features	Energy Flows
Air Handling Unit (Building)	Mass Flow Air
Air Handling Unit (Machine Shop)	Mass Flow Air
Machine Shop Occupants	Occupancy Gain
Sinks	Mass Flow Water
Central Plant	Steam Energy, Mass Flow Water

The proposed locations for the sensors in the first floor of the Hatch Centre can be observed in Figure 32.

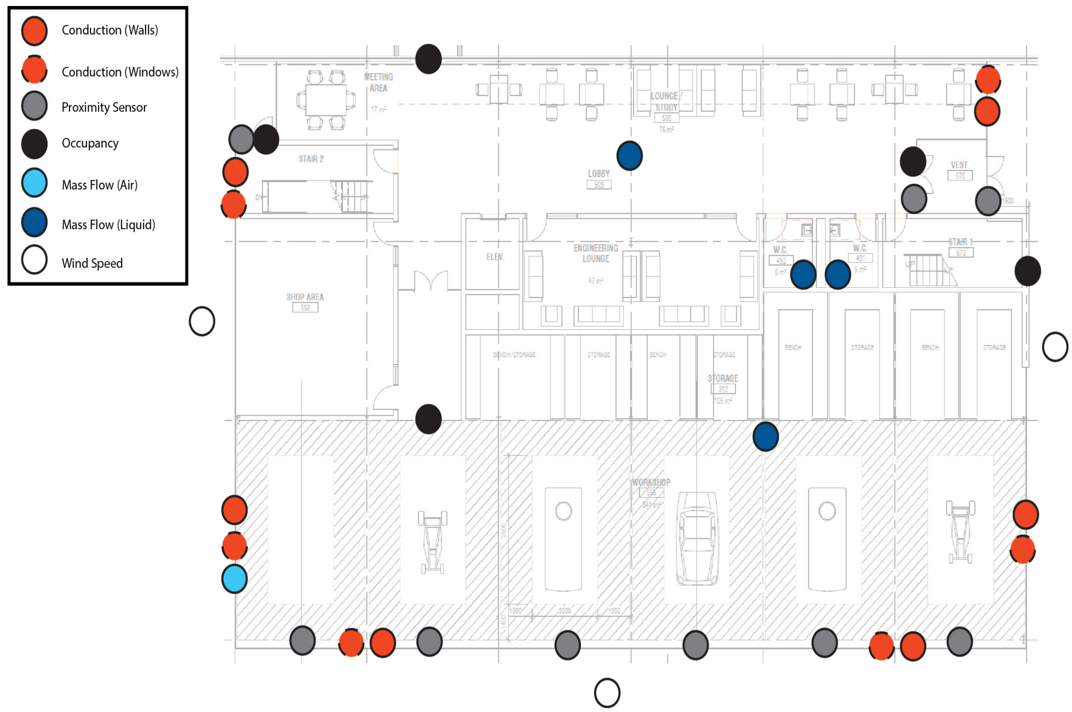

Figure 32: Proposed Location of Sensors for First Floor in Hatch Centre

5.4 Selection of Sensors

While Chapter 4 went over the process to select sensor types, no specific sensors were mentioned. This section will discuss the sensors chosen for the Hatch Centre for most of the sensors. Some sensors are considered to be a part of the regular building automation and energy management system.

When measuring the thermal energy in the different liquid-based systems in the building it is proposed to use energy valves from Belimo. These sensors utilize two thermistors, an ultrasonic flow meter and a self-actuating valve. The two thermistors are installed on either side of the energy transfer mechanism and the ultrasonic flowmeter measures the bulk flow rate. This in turn is used to calculate the heat transfer. Belimo valves were chosen due to their use of the two chosen sensor choices, thermistors and ultrasonic flow rates. They are also specifically designed to measure the energy flow through pipes and have an assortment of different monitoring devices that can fit many different types of pipes. This device doubles as the water temperature sensor.

In the case where thermal energy in the HVAC system is being measured the proposed sensor is the AD-1252 Thermal Dispersion Probe Airflow System. They are a thermal dispersion sensor with multiple sensors in the same horizontal plane; they are designed so that multiple horizontal planes can be installed in the same vertical plane to get an average value of air flow. These sensors are best suited for the job as they are specifically designed to measure the air flow and temperature of air in ducts. They come with a multiplexer that can be used to take the signal from the multiple point sensors and determine the average bulk flow. They are designed for minimal pressure drop which helps to keep the additional costs to the HVAC system low. As there are temperature sensors as well this device can automatically determine the amount of energy transferred throughout the HVAC system. This device doubles as the air temperature sensor.

It is proposed to measure conduction through the walls and windows with Hukseflux thermal sensors. For measuring conduction through the walls it is best to use the Hukseflux HFP01 and for the conduction through windows it is proposed to use the Hukseflux PU series of sensors. Both sensors work on the recommended principle of a thermopile. The HFP01 sensors are designed to work on walls and the specs are well within the limits discussed earlier in section 4.3. The thermal conductivity is such that the thickness of the aluminum substrate can be as much as 5 cm. The PU series is much thinner at 1 mm of thickness and has a thermal conductivity that is half as much as glass. These sensors are both well within the defined limits of a sensor as described earlier and as such they help to reduce the systematic error of the system to its minimum.

When measuring the solar gain through the windows the pyranometers are proposed to be the Zipp and Konen SP Lite 2. This is the pyranometer uses a small photovoltaic panel and a filter to ensure that light from the 400 – 1100 nm range transmits through to the sensor. This sensor has already been used in solar gain measurements by Bustamente et al where it was determined that it worked the same when compared to a more robust pyranometer [76].

The wind sensor is proposed to be the WindSonic 1-L from Campbell Scientific. It can operate between -35 to 70 ^{o}C and can measure wind speeds from 0 to 60 m/s. Both of these ranges are within the expected operating conditions for Hamilton, Ontario.

The webcam that is used for the occupancy sensors can be any webcam that is capable of continuous operation. The webcam must be fitted with an IR filter and an IR light source as shown in

Figure 33: Webcam with IR Filter and IR light Source

The sensors mentioned above are sensors that are specifically chosen for the Hatch Centre due to their quality. Throughout the research of this project it was found that these sensors had a wide range in quality and these sensors were the ones most used in different projects as well as current buildings. The only other sensors unaccounted for are the combined RH, CO_2, room temperature sensors. These sensors are generally interchangeable and any product that is capable of measuring all three is adequate for this system.

5.5 Building Specific Installation Instructions

It is important to know how many sensors are required to fully complete the measurement of each energy flow. By increasing the amount of sensing devices, there are fewer assumed energy flows which will in turn increase the accuracy of the system. However, excessive use of sensors in the system will increase the cost.

The budget is restrictive for this system, so it is important to not have too many sensors. The minimum amount of sensors that are capable of completing the energy balance should be utilized. There should be two conduction sensors placed on the exterior wall and window for the floor of the building. In total this is 18 wall conduction sensors and 18 window conduction sensors. They should be separated so that each sensor accounts for half of the conduction for its specified area. As the energy model indicated, this should not impact the accuracy of the system.

The amount of energy in the HVAC system will be determined at the two air handling units. It is proposed for there to be an ERV and if this occurs it is recommended to measure the thermal energy before and after the ERV in addition to the humidity sensor. The energy will also be measured as the conditioned air is vented to the outside environment. This HVAC system is proposed to have two air handling units and care should be taken to ensure that both units are having their energy monitored.

The occupancy will be measured at the entrances of the building, including the entrance to the adjacent building. The occupancy should also be measured in the machine shop specifically; as the activity being done in the machine shop is more strenuous than the activity in the rest of the building. The estimate will be closer to the actual energy gain from occupants in the building.

The solar gain pyranometers will be placed strategically around the top floor so that each direction the building is facing will be measured. In an effort to estimate shading four web cameras placed around the Hatch Centre. Two in the Mohawk at McMaster building across the street, one in the adjacent JHE building and one on the east side of the building on a pole 5 meters high. It is also possible for the cameras to be placed in the surrounding vegetation if it would offer a clearer view of the building. Of the two cameras in the building across the street one camera will be recording the south side and one will attempt to measure the solar gain on the roof of the building. These cameras will need to be placed indoors or inside a weatherproofed box. This system will also be measuring the indirect sunlight levels by placing a shaded pyranometer somewhere near the building. The cameras will measure where the building is shaded. Wherever a window is shaded it will assume that the same amount of energy is entering the building that is being measured with the direct shade sensor. Wherever direct sunlight is entering the building it will be assumed that it is the same amount of energy as what is being measured by associated pyranometer.

5.6 Uncertainty Analysis

The final step is to estimate the uncertainty of the system using the Monte Carlo error analysis. The analysis was completed as described in Chapter 4. An error accounting method was used to determine the total uncertainty involved in each measurement. An example of the error accounting method can be seen below.

Table 7: Uncertainty Accounting for measuring the Energy Transferred in the Mass Flow of Air in Ducts

Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
Calibration Uncertainty - T1 (Deg C)	.055	Normal	2	0.0275
Calibration Uncertainty - T2 (Deg C)	0.055	Normal	2	0.0275
Resolution - T1 (Deg C)	0.025	Rectangle	1.7	0.0144
Resolution - T2 (Deg C)	0.025	Rectangle	1.7	0.0144
Combined Uncertainty - T1				*0.0311*
Combined Uncertainty - T2				*0.0311*
Calibration Uncertainty* - Mdot (LPM)	2	Normal	2	1
Resolution - Mdot (LPM)	0.25	Rectangle	1.73	0.144
Combined Uncertainty - Mdot				*1.01*

The table shows the different sources of uncertainty that will be utilized in the different measurements, details of which are shown in Appendix E. From left to right the table determines the source of uncertainty with the sensor and what the nominal value of the uncertainty is from the material data sheet. The shapes of these uncertainties are estimated. All sources of uncertainty are assumed to have a normal distribution except for the error associated with resolution. This is due to the fact that it is equally likely that the measurement may fall anywhere within the resolution of the sensor whereas most other uncertainties follow a normal distribution [87]. The nominal uncertainty is then divided by a constant to get one standard deviation from the mean value. 2 is the value used for the normal distribution as it is assumed that the uncertainty is given to a 95% confidence interval. All of the uncertainty values are then added together in quadrature to have a combined uncertainty. This step was done for all measurements.

The governing equation for each measurement was written and the values were inserted.

For the mass flow of air this equation is:

$$Q = \dot{m} c_p \Delta T \tag{35}$$

On peak heating the inside temperature is 22 ^oC, the outside air in -15 ^oC. The flow rate is 5.4 m/s. The values chosen were given from the energy model mentioned before from the peak heating day. The values given from the model were assumed to be the mean value for the measurement and the total uncertainty for the measurement was assumed to be the standard deviation of the normal curve.

The total energy balance was calculated using the equation:

$$\Delta Q = \pm Q_{Generated} \pm Q_{Latent} \pm Q_{Conduction} \pm Q_{Infiltration} \pm Q_{Ventilation} + Q_{SolarGain} + Q_{Occupants} + Q_{Electrical} \quad (36)$$

Values were inserted for each parameter.

Ten thousand trials were run using the XLSim macro. This number was chosen as after this number there was no change in the result of the uncertainty. A total of 8% uncertainty to two standard deviations of confidence was determined after the analysis was completed.

5.7 Summary of Hatch Centre Sensor Array

Below is a summary table of all of the sensors required and their general location throughout the building. The first column shows the parameter that is being measured. The second column identifies what the type of sensor that should be used to measure that parameter. The third column identifies, roughly, where the sensors should be located in the building. The next column attempts to estimate the number of sensors required, and the final column estimates the uncertainty for each sensor as described in section 5.5 and Appendix E.

Table 8: Summary of Sensor Array for Hatch Centre

Parameter	Sensing Principle	Location	Estimated Quantity	Uncertainty
Mass Flow (Air)	Thermal Dispersion	At the Air Handling Unit, At the Output of Ventilation, Before and after the ERV	6	0.0371 ^oC of measured 1.00 m^3/s of measured
Mass Flow (Liquid)	Ultrasonic Flow	At the location where there is an air-to-water heat exchanger, at the location where flow of water needs to be controlled	10	0.232 ^oC of measured 1.00 m^3/s of measured

CO_2 Levels	NDIR	In room	30	N/A
Electric Load	Non-Socket Electronic, Feed-Through Meter	In the electrical room, Required for each different type of electric load	6	3% of measured
Relative Humidity	Resistive Type	In room	30	N/A
Room Temperature	Thermistor	In room	30	0.232 ^{o}C of measured
Thermal Conduction (Walls)	Heat Flux Transducer	On the inside of the exterior wall for the room	18	0.326 W/m^2 of measured
Thermal Conduction (Windows)	Heat Flux Transducer	On the inside of the exterior window for the room	18	0.834 W/m^2 of measured
Solar Heat Gain	Silicon PV Pyranometer	Minimum of one sensor per direction the building is pointing, Location determined by observations	3-6	0.339 W/m^2 of measured
Wind Velocity	Ultrasonic (2-Axis)	Attached to the building on each side	4	N/A
Occupancy	Optical Turnstile	On the entrance to the building and the entrance to the mechanical room (Not bay doors)	5	10% per person on occupant count 30% per person on metabolic rate
Infiltration (Building Leaks)	Tracer Gas Test	Takes place before building occupancy	N/A	3% on flow rate
Natural Ventilation	Proximity Sensors	On the exterior door (Includes bay doors)	7	5% on flow rate
Shading	Image Processing	Exterior to the building, one for each side	3	N/A

Chapter 6: Conclusion & Opportunity for Future Research

The objective of this research was to develop an energy monitoring system that would be capable of measuring a complete energy balance of a new commercial building with a targeted uncertainty of 10%. This was motivated due to a proposed engineering student centre at McMaster University as well as the lack of research currently being done on this topic. By improving the quality of information on building energy, it allows for improved research on energy modelling and conservation efforts. It also can contributes to the case for new conservation measures, including incentives and new technologies, by giving hard data on the energy flows and parameters of a building. The energy flows which affect a building’s energy flows can also become more readily identifiable. This can spur efforts to improve these energy flows. The results from the case study of the Hatch Centre can be used to turn the building into a living laboratory, encouraging the occupants to learn about building energy flows by occupying and observing the building’s features.

Current standards were used as the foundation for the process to complete the sensor array. The current standards only focus on the energy that can be consumed and generated on the building site. This research expanded upon the current standards by proposing methods of permanently measuring all of the energy flows that pass through the thermal envelope. The additional sensors are: solar heat gain, thermal conduction, occupancy gain, infiltration, and equipment gain. These flows are generally not measured on a permanent basis and it was required to alter current research so that the sensors measuring these flows could be a permanent fixture in the building.

The most important energy flows according to the energy model are infiltration and solar gain as they were the largest. The most sensitive to uncertainty are solar gain, infiltration, and occupancy. Infiltration was sensitive to uncertainty because it is proposed for the infiltration measurement to be taken during the commissioning phase and correlated to wind speed and pressure. Solar gain was sensitive to uncertainty due to the dependency on accurately estimating the shading on the building and the requirement for direct sunlight to always be measured inside the building. Occupancy was sensitive to the uncertainty as there is a 20% uncertainty associated with estimating the metabolic rates of occupants.

The first step in the process to develop the energy modelling system was to identify where all of the energy flows in a building take place and where these energy flows need to be measured. The zonal energy construct was introduced and its application to the development of the building energy monitoring system was discussed. The differences between an internal and external zone were also discussed, specifically the differences in the energy flows that affect the building's energy balance. After the zonal construct was discussed, the methodology for the selection of the sensors was introduced. For each type of measurement that was mentioned in the previous section, potential sensors were introduced and their merits were discussed. Based upon the selection process and the various relevant sensing qualities, a sensing type was chosen.

In addition to selecting each sensor, an energy model was developed to gain further insight to the estimates of the quantitative distribution of certain energy flows throughout the building and to see if position of the building or the individual sensor had a significant effect. For the cases that were investigated, the energy model assumed that there was no distribution in energy when looking at zones along the same face. In reality, this may not be the case for some scenarios. As such, strategies to account for these variations on the different faces of the building were developed. In addition to determining if any spatial distributions existed, the energy balance of the building was also determined. This will help to give insight on what the major drivers of the building energy use will be.

The largest building energy flow predicted by the energy model in both heating and cooling scenarios was determined to be the infiltration, which accounted for up to 50% of the driving force for heating or cooling within the building. This value must be verified for the building once the energy monitoring system has been installed. Conduction heat transfer through the windows and walls was about 10% of the energy flows. Since this amount was so small, the number of conduction sensors was reduced. The other energy flows were much larger, with each flow accounting for 20% or more of the overall energy flows. As a result the number of sensors for all other energy flows should remain high to capture any dissimilar energy flows throughout the building space.

Based on the results of the sensor selection and the energy model, installation instructions were proposed. The purpose of these installation best practices was to reduce the amount of systematic error in the system. In some scenarios the systematic error was not available, due to the system being a new design and no previous results being available. These installation instructions add value over the current standards, as most current standards do not give installation instructions. This can also lead to new types of sensors that are designed to measure building energy, which in turn can reduce the number of assumptions required for the measurement and can reduce the accuracy of the system.

The results from the energy model all fed into the error analysis which was completed using the Monte Carlo method. All of the information for the error analysis was determined through secondary sources. The error analysis was run for the heating using conservative estimates for the typical heating and cooling values. The uncertainty analysis determined that the uncertainty of the system was 10%.

6.1 Opportunities for Future Research

The results discussed allow for many different avenues of research for the future. Some systems were suggested specifically for this research project and their uncertainty was estimated, but not tested. Rigorous testing of the shading system is required before it is implemented in a commercial setting. The infiltration system, while adequate for these purposes, is generally a one-time measurement. Either the infiltration method needs to be developed further so that each measurement is autonomous and simpler to implement, or a new type of infiltration measurement needs to be developed that can be used as a permanent fixture within the building.

This research also logically leads into a project where this system is implemented into a building and the inputs and outputs are measured to ensure that all of the energy flows throughout the building are being accounted for. This project would then be able to more accurately determine the error. This is due to the fact that a type B Monte Carlo error analysis is using the uncertainty associated with the data sheets of each sensors as well as the maximum amount of systematic error that is possible for each measurement assuming perfect installation. If the installation is poor or different sensors are picked, the uncertainty of the system may change. By directly measuring the uncertainty of the sensor array it is possible to get a more accurate measure of the uncertainty after installation. This will help with any research that may be done due to the sensor array being in place.

Upon implementation in a building and the accuracy of the system is established, research can be completed on the integration of highly detailed measurements and control systems. This can help with determining which sensors can aid in controlling an energy monitoring system. The use of predictive controls can also be utilised. If a system is able to understand when a zone is about to be occupied, or if a specific weather front is coming in to the building, it can account for that change before it occurs, mitigating its effect on a building.

Other applications would be testing when building materials fail and determining different benchmarks to test for when this occurs. For example, if the seal in the window fails and argon leaks out, the conduction will increase as a result. Since all buildings do not have window conduction sensors, it is possible that a different parameter will change as a result. If multiple changing parameters, the most cost effective option can become a standard measurement in building automation systems that allows for to detection of these failures the moment they occur. Moreover, immediate failure detection can potentially reduce the energy consumption associated with failed systems.

There is also the potential for new technologies to be created due to this research. With more understanding of the flows of building energy, better technologies can be created to reduce these energy flows. For example, this research determined that infiltration is a large reason for building energy consumption. By disseminating and this information to the general public, it may become more attractive to create a technology that can reduce the infiltration energy flow.

In order for these new technologies to gain acceptance, and to increase the use of existing technologies, new research that looks at changing incentive policies should be completed. In Ontario, for the current energy plan to be successful there must be significant conservation savings. Currently, to increase the savings from conservation there are incentives that encourage spending on energy conservation measures. These incentives are all based on electricity and natural gas consumption. If research can be conducted that shows a specific energy flow is the cause of consumption and there is a way to permanently measure this flow, the incentives can be altered to incentivize different designs. For example, if solar gain is a large reason for cooling loads in the summer, when electricity usage is very close to peak capacity, an improved incentive plan could be based around solar heat gain, as opposed to electrical consumption. This can improve the behaviour of building designers and operators as it gives a direct reason to use technologies such as active shading.

The use of a sensor array that can measure a complete energy balance will help to improve research on building design, building technologies, and building automation systems. With increased information on building energy flows incentive programs can better target the energy flows that have the greatest impact on energy consumption in buildings.

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Appendix A – Energy Model Description

All tables courtesy of http://www.comnet.org/mgp/content/exterior-walls?purpose=0 [88]

Sample constructions that were used in the energy model are also included.

Weather Data

Used Toronto Pearson Airport Location

Building Envelope Construction

Exterior Wall Construction

Applicable Standard	Space Category	Climate Zone	Standard Design	
			Minimum Insulation	Maximum Assembly
90.1 - 2001	Nonresidential	1-4	R-13	U-0.124
		5,6	R-13 + R-3.8 c.i.	U-0.084
		7,8	R-13 + R-7.5 c.i.	U-0.064
	Residential	1,2	R-13	U-0.124
		3	R-13 + R-3.8 c.i.	U-0.084
		4- 7	R-13 + R-7.5 c.i.	U-0.064
		8	R-13 + 10.0 c.i.	U-0.055
	Semi-Heated	1- 3	NR	U-0.352
		4 - 8	R-13	U-0.124
90.1 - 2007	Nonresidential	1,2	R-13	U-0.124
		3	R-13 + R-3.8 c.i.	U-0.084
		4-8	R-13 + R-7.5 c.i.	U-0.064
	Residential	1	R-13	U-0.124
		2-6	R-13 + R-7.5 c.i.	U-0.064
		7	R-13 +15.6 c.i.	U-0.042
		8	R-13 + R-18.8 c.i.	U-0.037
	Semi-Heated	1	NR	U-0.352
		2-7	R-13	U-0.124
		8	R-13 + R-3.8 c.i.	U-0.084

To get this wall composition it is recommended to have

Construction	Layer	Thickness (inch)	Conductivity (Btu/h ft F)	Density (lb/ft²)	Specific Heat (Btu/lb F)	R-value (ft²·°F·h/Btu)	U-factor (Btu/ft²·°F·h)
Wall R-13 + R-7.5	Air film					0.17	
	Stucco	0.400	0.4167	116	0.2	0.08	
	R-7.5 continuous insulation	1.800	0.0200	1.8	0.29	7.50	
	Gypsum board	0.625	0.0930	50	0.2	0.56	
	R-13 insulation/steel framing					6.00	
	Gypsum board	0.625	0.0930	50	0.2	0.56	
	Interior air film					0.68	
	Total for assembly					15.55	0.64
Wall R-13 + R-3.8	Air film					0.17	
	Stucco	0.400	0.4167	116	0.2	0.08	
	R-3.8 continuous insulation	0.912	0.0200	1.8	0.29	3.80	
	Gypsum board	0.625	0.0930	50	0.2	0.56	
	R-13 insulation/steel framing					6.00	
	Gypsum board	0.625	0.0930	50	0.2	0.56	
	Interior air film					0.68	
	Total for assembly					11.85	0.84
Wall R-13	Air film					0.17	
	Stucco	0.400	0.4167	116	0.2	0.08	
	Gypsum board	0.625	0.0930	50	0.2	0.56	
	R-13 insulation/steel framing					6.00	
	Gypsum board	0.625	0.0930	50	0.2	0.56	
	Interior air film					0.68	
	Total for assembly					199.95	0.124

Wall Construction is

1. Outside airgGap
2. F07 25 mm stucco
3. I05 50mm insulation
4. Steel Framing Insulation
5. Gypsum or Plaster Board
6. Inside air gap

<u>Roof Construction</u>

ASHRAE 90.1 2010 Roof Standard

Applicable Standard	Space Category	Climate Zone	Standard Design	
			Minimum Insulation	Maximum Assembly
90.1 – 2001	Nonresidential	1-7	R-15 c.i.	U-0.063
		8	R-20 c.i.	U-0.048
	Residential	1,2,3,4,5,6,7	R-15 c.i.	U-0.063
		8	R-20 c.i.	U-0.048
	Semi-Heated	1	NR	U-1.282
		2,3,4	R-3.8 c.i.	U-0.218
		5,6,7	R-5.0 c.i.	U-0.173
		8	R-10.0 c.i.	U-0.093
90.1 – 2007 and 90.1 – 2010	Nonresidential	1	R-15 c.i.	U-0.063
		2-8	R-20 c.i.	U-0.048
	Residential	1-8	R-20 c.i.	U-0.048
	Semi-Heated	1, 2	R-3.8 c.i.	U-0.218
		3, 4	R-5.0 c.i.	U-0.173
		5	R-7.6 c.i	U-0.119
		6,7	R-10.0 c.i.	U-0.093
		8	R-15.0 c.i.	U-0.063

To get this the recommended composition is:

Construction	Layer	Thickness (inch)	Conductivity (Btu/h ft F)	Density (lb/ft^2)	Specific Heat (Btu/lb F)	R-value ($ft^2 \cdot °F \cdot h/Btu$)	U-factor ($Btu/h-ft^2-F$)
Roof R-20 c.i.	Exterior air film					0.17	
	Roofing membrane					0.00	
	R-20 continuous insulation	4.8	0.02	1.8	0.29	20.00	
	Steel deck	0.06	26	480	0.10	0.00	
	Interior air film					0.61	
	Total for assembly					20.78	0.048
Roof R-15 c.i.	Exterior air film					0.17	
	Roofing membrane					0.00	
	R-15 continuous insulation	3.6	0.02	1.8	0.29	15.00	
	Steel deck	0.06	26	480	0.10	0.00	
	Interior air film					0.61	
	Total for assembly					15.78	0.063

Roof Construction is

1. Outside airgGap
2. F13 Built-up Roofing
3. I03 Roof insulation
4. Steel Deck
5. Inside air gap

<u>Doors</u>

Assume doors are swinging and not sliding

Applicable Standard	Swinging or Non-swinging	Climate Zone	Space Category		
			Nonresidential	Residential	Semi-Heated
ASHRAE Standard 90.1 - 2001	Swinging	1- 5	0.700	0.700	0.700
		6, 7	0.700	0.500	0.700
		8	0.500	0.500	0.700
	Non-swinging	1, 2	1.450	1.450	1.450
		3- 5	1.450	0.500	1.450
		6- 8	0.500	0.500	1.450
ASHRAE Standard 90.1 - 2007	Swinging	1- 4	0.700	0.700	0.700
		5, 6	0.700	0.500	0.700
		7, 8	0.500	0.500	0.700
	Non-swinging	1	1.450	1.450	1.450
		2, 3	1.450	0.500	1.450
		4	1.500	0.500	1.450
		5- 7	0.500	0.500	1.450

Fenestration

Vertical Fenestration (I.e. windows)

Building type	Fenestration Type	Climate Zone	Standard Design		
			U-factor	SHGC	VT
Nonresidential	Non-Metal Framing	1	1.20	0.25	0.32
		2	0.75	0.25	0.32
		3	0.65	0.25	0.32
		4	0.40	0.40	0.51
		5,6	0.35	0.40	0.51
		7,8	0.35	0.45	0.57
	Metal Framing Curtainwall/ Storefront	1	1.20	0.25	0.32
		2	0.70	0.25	0.32
		3	0.60	0.25	0.32
		4	0.50	0.40	0.51
		5,6	0.45	0.40	0.51
		7,8	0.40	0.45	0.57
	Metal Framing Entrance Door	1	1.20	0.25	0.32
		2	1.10	0.25	0.32
		3	0.90	0.25	0.32
		4	0.85	0.40	0.51
		5,6	0.80	0.40	0.51
		7,8	0.80	0.45	0.57
Nonresidential (Continued)	Metal Framing All Other	1	1.20	0.25	0.32
		2	0.75	0.25	0.32
		3	0.65	0.25	0.32
		4	0.55	0.40	0.51
		5,6	0.55	0.40	0.51
		7,8	0.45	0.45	0.57

Low-E Glass – WindowMaterial:Glazing

LoE Clear 6MM

Argon Gas – WindowMaterial:Gas

Argon 13MM

Clear Glass – WindowMaterial:Glazing

Clear 3MM

Skylights

Proposed Design	Applicable Standard	Climate Zone	% of Roof	Standard Design		
				U-factor	SHGC	VT
Glass Skylight with Curb	90.1 – 2001 & 90.1 - 2007	1,2	0-2.0%	1.98	0.36	0.46
			2.1-5.0%	1.98	0.19	0.24
		3 (A,B) - (all climate zone 3 for 2007)	0-2.0%	1.17	0.39	0.50
			2.1-5.0%	1.17	0.19	0.24
		3 (C) (2001 only)	0-2.0%	1.98	0.61	0.77
			2.1-5.0%	1.98	0.39	0.50
		4,5	0-2.0%	1.17	0.49	0.62
			2.1-5.0%	1.17	0.39	0.50
		6	0-5.0%	1.17	0.49	0.62
		7	0-2.0%	1.17	0.68	0.68
			2.1-5.0%	1.17	0.64	0.64
		8	0-2.0%	0.98	0.55	0.63
Plastic Skylight with Curb	90.1 - 2001 & 90.1 - 2007	1	0-2.0%	1.90	0.34	0.41
			2.1-5.0%	1.90	0.27	0.32
		2	0-2.0%	1.90	0.39	0.47
			2.1-5.0%	1.90	0.34	0.41
		3,4	0-2.0%	1.30	0.65	0.78
			2.1-5.0%	1.30	0.34	0.41
		5	0-2.0%	1.10	0.77	0.92
			2.1-5.0%	1.10	0.62	0.74
		6	0-2.0%	0.87	0.71	0.85
			2.1-5.0%	0.87	0.58	0.70
		7	0-2.0%	0.87	0.77	0.92
			2.1-5.0%	0.87	0.71	0.85
		8	0-2.0%	0.61	0.59	0.64
Skylight without Curb	90.1 – 2001 & 90.1 – 2007	1,2	0-2.0%	1.36	0.36	0.46
			2.1-5.0%	1.36	0.19	0.24
		3 (A,B) - (all climate zone 3 for 2007)	0-2.0%	0.69	0.39	0.50
			2.1-5.0%	0.69	0.19	0.24
		3 (C) (2001 only)	0-2.0%	1.36	0.61	0.77
			2.1-5.0%	1.36	0.39	0.50
		4,5	0-2.0%	0.69	0.49	0.62
			2.1-5.0%	0.69	0.39	0.50
		6	0-5.0%	0.69	0.49	0.62
		7	0-2.0%	0.69	0.68	0.68
			2.1-5.0%	0.69	0.64	0.64
		8	0-5.0%	0.58	0.55	0.63

Below Grade Walls

Applicable Standard	Space Category	Climate Zone	Standard Design	
			Minimum Insulation	C-Factor
90.1 - 2001	Nonresidential	1- 6	NR	1.140
		7, 8	R-7.5 c.i.	0.119
	Residential	1-5	NR	1.140
		6- 8	R-7.5 c.i.	0.119
	Semi-Heated	1-8	NR	1.140
90.1 - 2007	Nonresidential	1- 4	NR	1.140
		5678	R-7.5 c.i.	0.119
	Residential	1-3	NR	1.140
		456	R-7.5 c.i.	0.119
		7	R-10 c.i.	0.092
		8	R-12.5 c.i.	0.075
	Semi-Heated	1- 8	NR	1.140

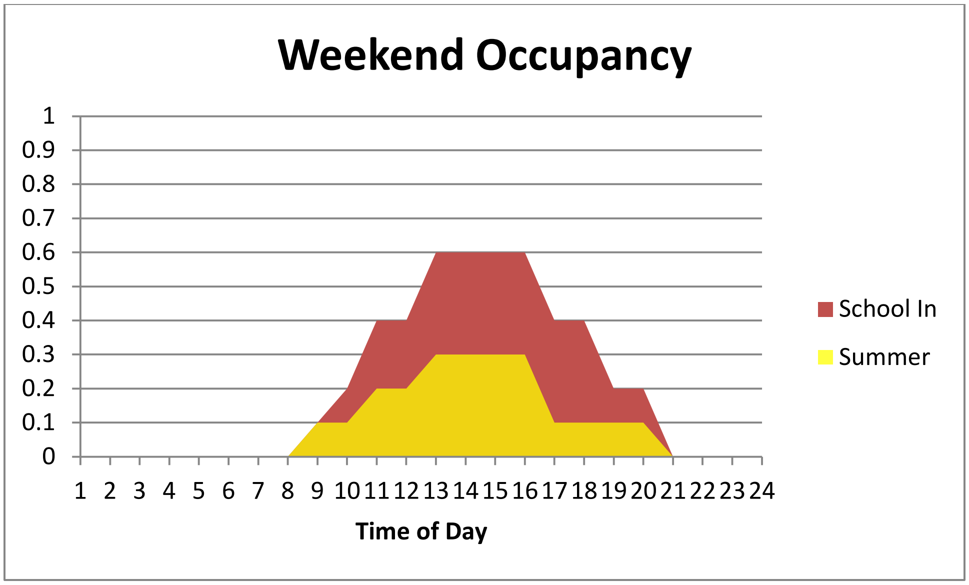
To get this composition it is recommended to use

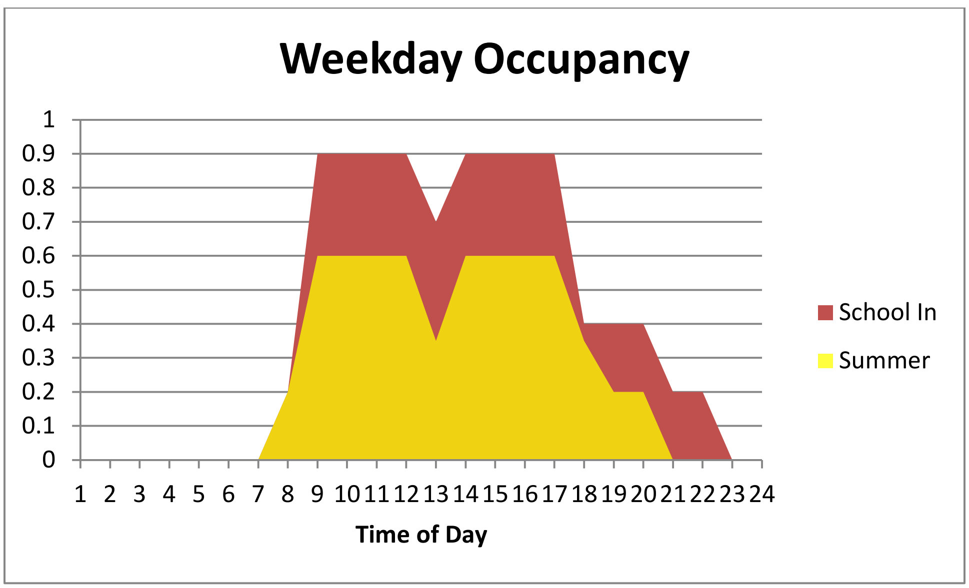
Construction	Layer	Thickness (inch)	Conductivity (Btu/h ft F)	Density (lb/ft²)	Specific Heat (Btu/lb F)	R-value (ft²·°F·h/Btu)	C-factor (Btu/ft²·°F·h)
NR	115 lb/ft3 CMU, solid grout	8	0.45	115	0.20	0.87	1.140
R-7.5 c.i.	115 lb/ft3 CMU, solid grout	8	0.45	115	0.20	0.87	
	R-10 continuous insulation	1.8	0.02	1.8	0.29	7.50	
	Total assembly					8.37	0.119
R-10 c.i.	115 lb/ft3 CMU, solid grout	8	0.45	115	0.20	0.87	
	R-10 continuous insulation	2.4	0.02	1.8	0.29	10.00	
	Total assembly					10.87	0.092
R-12.5 c.i.	115 lb/ft3 CMU, solid grout	8	0.45	115	0.20	0.87	
	R-10 continuous insulation	3.0	0.02	1.8	0.29	12.50	
	Total assembly					13.37	0.075

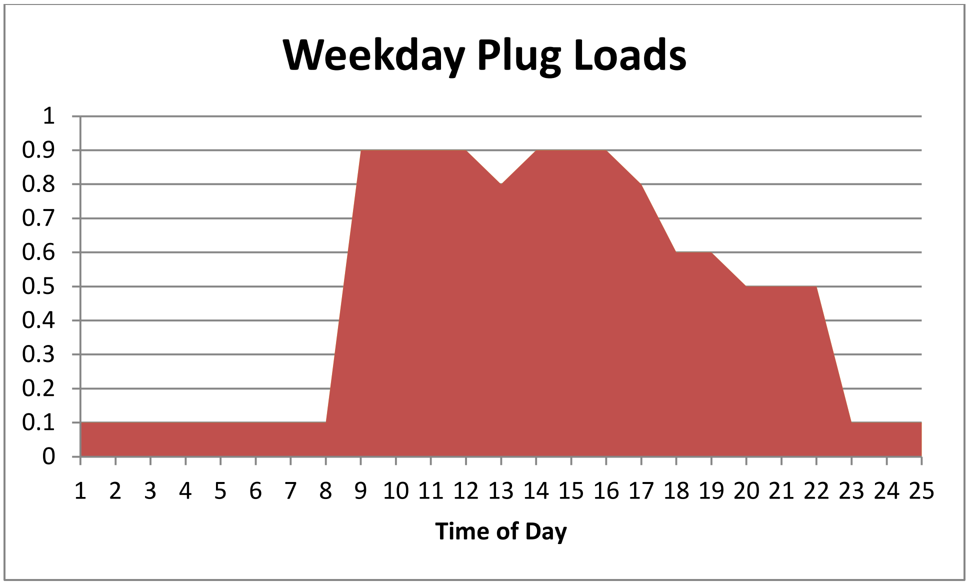
<u>Slab in Contact with Ground</u>

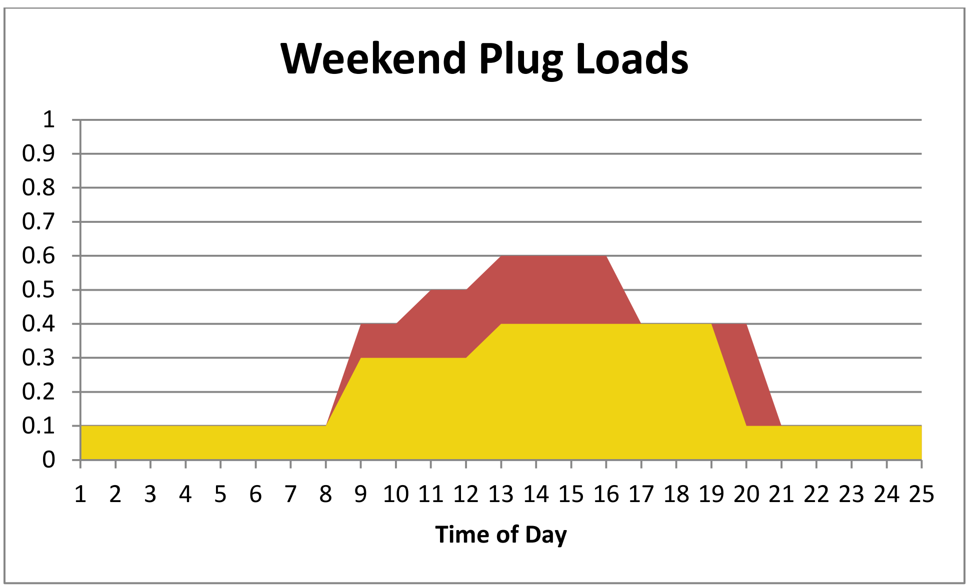
90.1 – 2007	Unheated	Nonresidential	1-5	NR	0.730
			6	R-10 for 24 in. vertical	0.540
			7,8	R-15 for 24 in. vertical	0.520
		Residential	1- 3	NR	0.730
			4, 5	R-10 for 24 in. vertical	0.540
			6, 7	R-15 for 24 in. vertical	0.520
			8	R-20 for 24 in. vertical	0.510
		Semi-Heated	1- 8	NR	0.730
	Heated	Nonresidential	1, 2	R-7.5 for 12 in. vertical	1.020
			3	R-10 for 24 in. vertical	0.900
			4- 6	R-15 for 24 in. vertical	0.860
			7	R-20 for 24 in. vertical	0.843
			8	R-20 for 48 in. vertical	0.688
		Residential	1, 2	R-7.5 for 12 in. vertical	1.020
			3	R-10 for 24 in. vertical	0.900
			4, 5	R-15 for 24 in. vertical	0.860
			6- 8	R-20 for 48 in. vertical	0.688
		Semi-Heated	1- 6	R-7.5 for 12 in. vertical	1.020
			7, 8	R-10 for 24 in. vertical	0.900

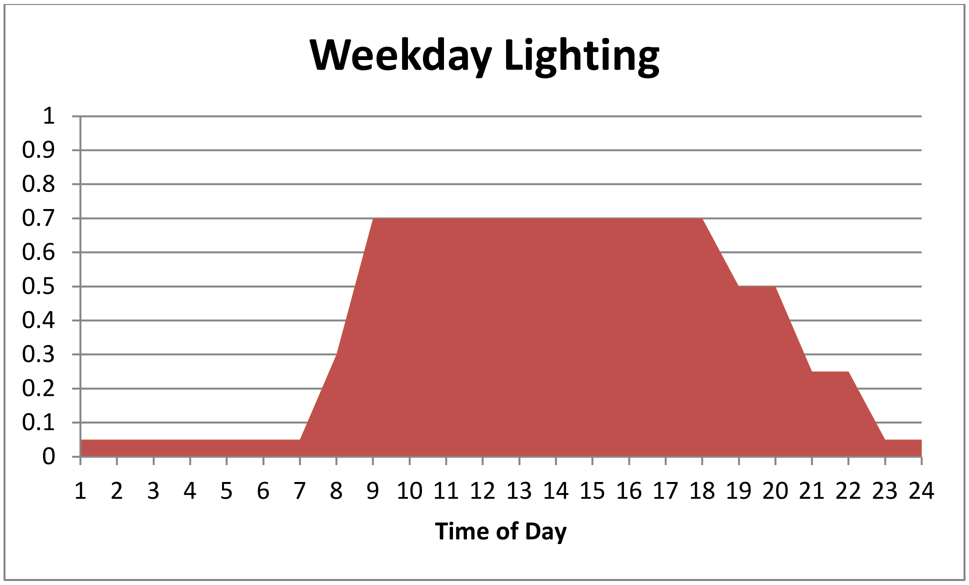
Below is the expected scheduling for the building for occupancy, plug loads, lighting, when the HVAC system is on. In some instances the schedule is split between when school is in which is between September 1^{st} to April 30^{th} and when it is summer time, between May 1^{st} and August 31^{st}.

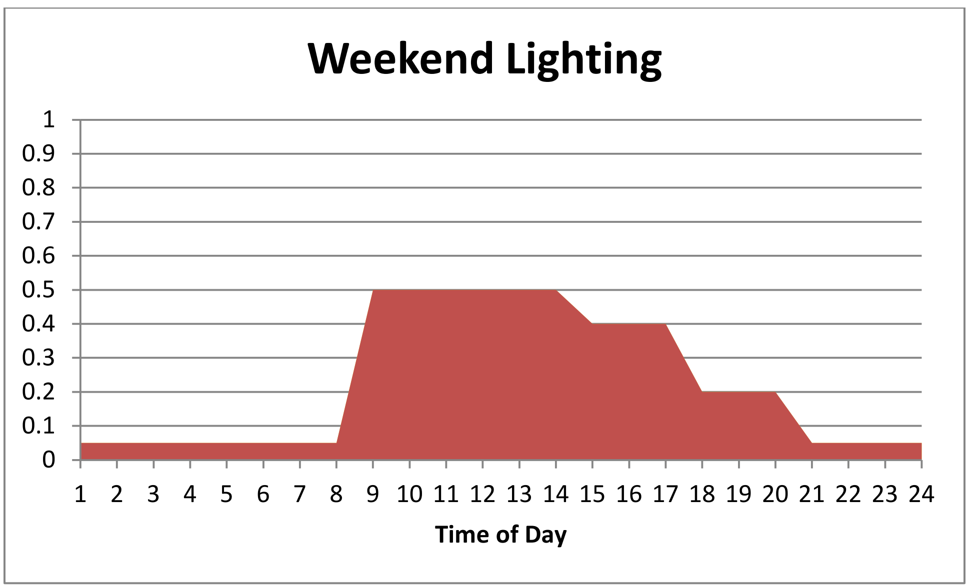

Weekend Occupancy
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time of Day
School In
Summer

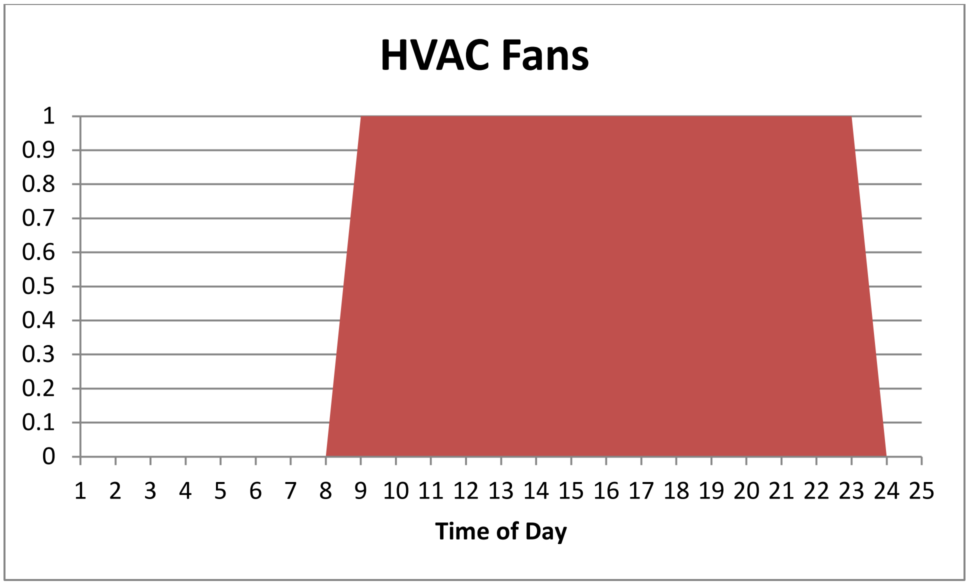

Weekday Occupancy
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time of Day
School In
Summer


Weekday Plug Loads
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time of Day


Weekend Plug Loads
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time of Day


Weekday Lighting
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time of Day


Weekend Lighting
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time of Day


HVAC Fans
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time of Day

Appendix B – Decision Matrices for Sensors

Table 9: Decision Matrix for Temperature Sensors

Factor	Weight	Thermistor	Thermocouple	IR	RTD
Robustness	9	8	6	5	8
Reliability	9	7	8	9	7
Cost	7	6	7	2	4
Accuracy	5	8	7	5	9
Score		**217**	210	172	215

Table 10: Decision Matrix for Liquid Flow

Factor	Weight	Differential Head	Turbine	Electromagnetic	Vortex Shedding	Ultrasonic
Robustness	9	4	7	5	8	6
Reliability	9	10	4	9	7	8
Cost	7	5	10	4	4	8
Accuracy	5	9	5	8	10	7
Score		206	194	194	213	**217**

Table 11: Decision Matrix for Air Flow

Factor	Weight	Pitot Tube	Hot Wire	Thermal Dispersion
Robustness	9	8	7	9
Reliability	9	7	8	9
Cost	7	6	7	5
Accuracy	5	8	7	10
Score		221	219	**247**

Table 12: Decision Matrix for Wind Measurement

Factor	Weight	Vane/Cup	Ultrasonic
Robustness	9	8	7
Reliability	9	4	8
Cost	7	10	5
Accuracy	5	6	8
Score		208	**210**

Table 13: Decision Matrix for Occupancy Gain

Factor	Weight	Thermal Imaging	Computer Imaging	Optical Turnstile
Robustness	9	9	8	7
Reliability	9	6	6	8
Cost	7	2	3	8
Accuracy	5	8	7	4
Score		189	182	**211**

Appendix C – Calibration of Sensors

This section will look at the required calibration for each of the sensors where required.

Temperature Sensors

The temperature-resistance curve of a thermistor can be described by the use of the Steinhart-Hart equation. This equation is:

$$\frac{1}{T} = A + B \cdot \ln R_T + C \cdot (\ln R_T)^3$$

where T is the temperature in Kelvin, R_T is the resistance of the thermistor at temperature T, and A, B, C are constants. For this equation there are three unknowns, so to solve for A, B, and C the thermistor must be tested at three different temperatures. The sensing device should be wrapped to avoid getting it wet. This may cause oxidation of the sensor.

Liquid Mass Flow Meters

According to the manufacturer, the Belimo energy valves which were chosen for the sensor array are shipped fully calibrated and do not require future calibration [89].

If a different sensor is chosen and calibration has not been completed, the NIST recommends utilizing a static gravimetric method. A schematic of the system can be observed below.

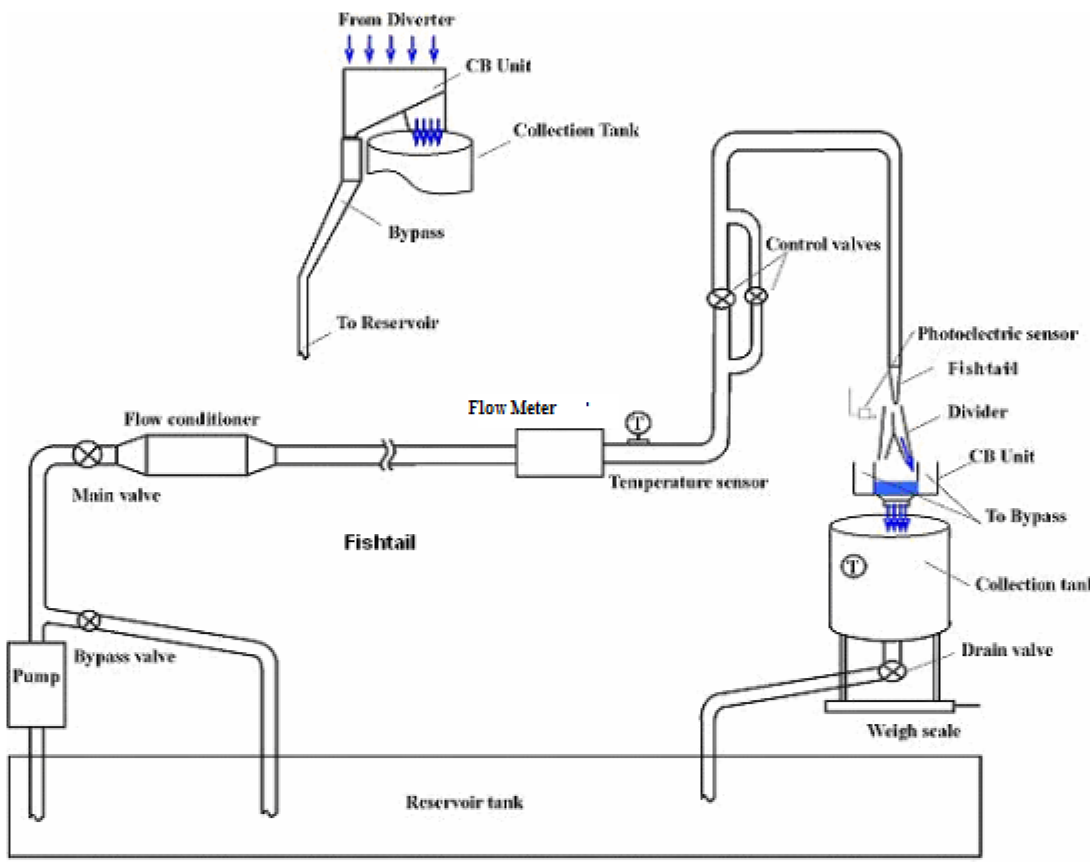


Figure 34: Schematic of the system used for the static gravimetric method

The method works by calibrating the meter over a measured period of time under steady flow, pressure and temperature conditions. The mass of water used during this time is collected. A second, calibrated flowmeter can be used to test the flow rate and to determine the stability of the flow rate over time. The average mass flow rate through the system can be determined through the equation:

$$\dot{m} = \frac{M}{\Delta t} + (\rho_2 - \rho_2)V_1$$

where M is collected mass and Δt is collection time. The inventory volume, V_1 is the volume of piping between the meter under test and the standard used, at the end of the pipe, to measure the flow. The densities ρ_1 and ρ_2 are those in the inventory volume at the beginning and end of the collection interval. This equation applies to an idealized set of conditions: (1) the flow velocity profile exiting the pipe and entering the standard is symmetric with respect to the middle of the fishtail, and (2) the motion of diverter in the middle of the water jet is horizontal. More details of this system can be seen in [90].

Air Mass Flow Meters

Calibrating an airflow sensor can be completed using an open-loop method or a closed-loop method. The open-loop method is much simpler to implement and as such it will be discussed here.

A schematic of a typical open-loop tester can be observed below.

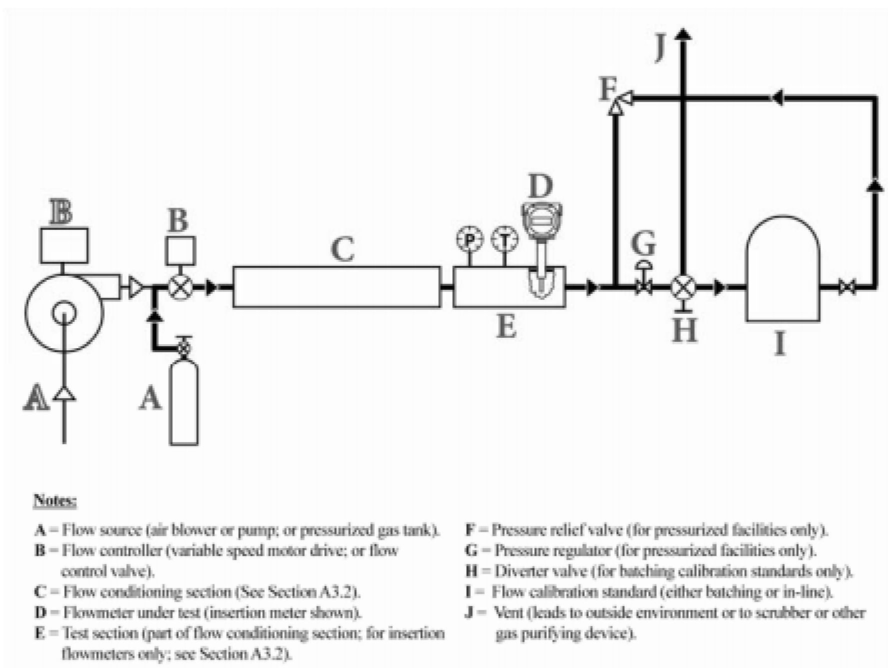


Figure 35: Schematic of System Required for an Open-Loop Tester for Airflow

It should be noted that for air velocities less than 5 m/s, in an open loop system, the flow rate can be altered due to the opening and closing of doors and other changes in pressure and temperature in the room. During the calibration process, care should be taken to minimize these effects.

As this type of system calibrates the air flow sensor with a more accurate air flow sensor, it is important for the reference sensors to have accuracy that is at least 3 times better than the tested sensor. For more information on the procedure refer to [91].

Heat Flux Sensor

To calibrate the heat flux sensors it is recommended to use a heat flow meter method. The method consists of a constant heat source and a test assembly. This can be observed below.

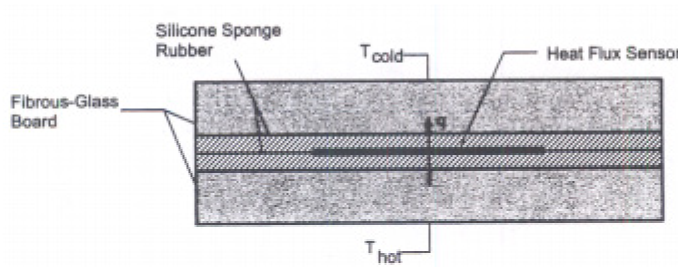


Figure 36: Test assembly for heat flux sensor calibration

The heat flux sensor is sandwiched between two silicone sponge rubber plates. The temperature must be measured on the hot and cold sides. As the conductance of the materials is known and the temperature is being measured the heat flux can be determined through the equation:

$$q = C\Delta T$$

where q is the heat flux being measured, C is the total conductance and ΔT is the temperature difference between the hot and cold side. The apparatus much reach a steady state, which is estimate to take 4 hours. The area of the plates is recommended to be 610x610 mm. Each silicon rubber layer is recommended to be 3 mm thick and have a density of 470 kg/m^3. The fibrous-glass thermal insulation layers are recommended to have a thickness of 25 mm and a density of 135 kg/m^3. The output from the transducer can be compared to the calculated heat flux at different points to complete the calibration curve. More details can be found at [92].

Solar Gain Sensors

The majority of ways to calibrate solar gain sensors is to complete a side-by-side comparison to a reference measurement where the calibration curve is known and is at least as accurate as the tested sensor. This particular method utilizes two sensors with an artificial sun to allow the test to be completed indoors. The artificial sun is a 150 W Metal-Halide high-pressure gas discharge lamp with voltage stabilization. Behind the lamp is a reflector of diameter 16.2 cm. The reflector is placed 115 cm above the sensors to produce a vertical beam. The irradiance is approximately 500 W/m^2.

The two sensors are placed on a rotating table. This allows the sensors to change reference positions. The sensors are illuminated for one minute and the output voltages of both sensors are measured. These values are labeled as R and T, with R being the value of the reference sensor and T being the tested sensor.

The sensors are then covered and allowed no light for one minute. After the time has elapsed the two voltages are again measured. The values are the zero offsets and are RE and TE for the reference and tested sensor respectively. From this, you can get the resultant R1 and T1 by subtracting the reference voltage from the illuminated output voltage.

The positions of the sensors are switched and the process is repeated, yielding R2 and T2 this time. The sensitivity of the tested sensor can then be determined through the equation:

$$ST = SR \cdot \frac{(T1 + T2)}{(R1 + R2)}$$

where SR is the sensitivity of the reference meter. Finally a check on errors can be completed to ensure that the calibration was completed correctly. It is recommended to re-do the calibration if the following expression is not true:

$$0.98 < \frac{(R1 \cdot T1)}{(R2 \cdot T2)} < 1.02$$

For more details refer to [93].

Wind Speed Sensors

To calibrate a wind speed sensor it is required to use a wind tunnel and Pitot tubes to measure the wind speed. Before the calibration test can start all transducers and measuring equipment shall have traceable calibrations. Calibration certificates and reports shall contain all relevant traceability information. The pitot tubes used must be calibrated for appropriate wind speed ranges and be documented. Prior to calibration, the setup must be verified by means of comparative calibration of a reference anemometer. The repeatability of the calibration shall be verified. Finally an assessment of measurement uncertainty shall be carried out in accordance with ISO guidelines.

The anemometer should be run in the wind tunnel for 5 minutes to reach a steady state temperature. Then the wind speed should start at 4 m/s and increase to 16 m/s with steps of 1 m/s or less. Once at 16 m/s the wind speed should be decreased back to 4 m/s using the same time step. This helps to account for hysteresis effects. The sampling frequency must be at least 1 Hz with an interval of at least 30 s.

The air density is calculated from the equation:

$$\rho = \frac{1}{T}\left(\frac{B}{R_o} - \varphi \cdot P_w\left(\frac{1}{R_o} - \frac{1}{R_w}\right)\right)$$

Where B is the barometric pressure in Pa, T is the absolute temperature in K, φ is the relative humidity (range 0 to 1), R_o is the gas constant of dry air (287.05 J/kgK), R_w is the gas constant of water vapour (461.5 J/kgK) and P_w is the vapour pressure in Pa. The water vapor pressure is defined by:

$$P_w = 0.0000205^{0.0631846T}$$

Finally, the wind speed can be calibrated by using the equation

$$\overline{v} = k_b \frac{1}{n}\sum_{i=1}^{n}\sqrt{\frac{2k_c}{C_h} \cdot \frac{ref,i}{\rho}}$$

Where Ch is the Pitot tube head coefficient, k_c is the wind tunnel calibration factor, k_b is the blockage correction factor, and n is the number of samples within the sampling interval. For more details refer to [94].

The other sensors listed in this report do not require calibration due to their sensing principles.

Appendix D – Results of Energy Model

The results of the energy model are shown below. The results are split between the heating and cooling modes of the building as well as by month.

Cooling							
Month	June	July	Aug	Sept	Oct	Total	Percent
Flows that Add Heat (Energy (J))							
Equipment	1.41E+10	1.35E+10	1.44E+10	1.44E+10	6.96E+08	5.72E+10	7%
Lighting	2.63E+10	2.54E+10	2.68E+10	2.59E+10	2.58E+10	1.30E+11	17%
Infiltration Gain	5.63E+06	2.37E+09	6.60E+09	6.50E+10	6.00E+08	7.46E+10	9%
Ventilation	0.00E+00	5.02E+09	1.38E+10	9.65E+09	1.58E+09	3.01E+10	4%
People	2.00E+10	1.90E+10	2.00E+10	1.92E+10	3.40E+10	1.12E+11	14%
SHG	6.88E+10	6.85E+10	7.07E+10	7.00E+10	6.70E+10	3.45E+11	44%
Window Conduction	0.00E+00	5.10E+09	8.30E+09	7.40E+09	3.30E+09	2.41E+10	3%
Wall Conduction	0.00E+00	5.94E+08	3.65E+09	3.16E+09	0.00E+00	7.40E+09	1%
Roof Conduction	0.00E+00	1.16E+09	2.30E+09	1.87E+09	0.00E+00	5.33E+09	1%
Flows that Remove Heat (Energy (J))							
Sensible Cooling Load	4.98E+10	8.06E+10	1.06E+11	9.70E+10	7.24E+10	4.06E+11	58%
Infiltration Heat Loss	6.03E+10	3.16E+10	1.75E+10	2.25E+10	4.50E+10	1.77E+11	25%
Ventilation	1.87E+10	1.14E+10	7.51E+09	8.32E+09	1.63E+10	6.23E+10	9%
Window Conduction	9.44E+09	5.39E+09	3.89E+09	4.48E+09	8.03E+09	3.12E+10	4%
Wall Conduction	5.04E+09	0.00E+00	0.00E+00	0.00E+00	2.46E+09	7.49E+09	1%
Roof Conduction	1.02E+09	0.00E+00	0.00E+00	0.00E+00	8.40E+08	1.86E+09	0%
Ground Conduction	2.46E+09	3.02E+09	3.50E+09	3.45E+09	2.73E+09	1.52E+10	2%

Heating									
Month	Jan	Feb	Mar	Apr	May	Nov	Dec	Total	%
Flows that Add Heat (Energy (J))									
Equipment	1.38E+10	1.53E+10	1.36E+10	1.48E+10	1.47E+10	1.53E+10	1.42E+09	8.89E+10	6%
Lighting	2.68E+10	2.68E+10	2.40E+10	2.60E+10	2.58E+10	2.68E+10	2.49E+10	1.81E+11	12%
Infiltration Gain	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
Ventilation	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
People	3.53E+10	3.53E+10	3.13E+10	3.38E+10	3.40E+10	3.53E+10	3.25E+10	2.38E+11	16%
SHG	3.09E+10	4.16E+10	4.78E+10	5.70E+10	6.12E+10	5.40E+10	2.86E+10	3.21E+11	21%
Window Conduction	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
Wall Conduction	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
Roof Conduction	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0%
Sensible Heating Energy	1.33E+11	1.60E+11	1.38E+11	1.00E+11	4.80E+10	3.50E+10	7.50E+10	6.89E+11	45%
Flows that Remove Heat (Energy (J))									
Infiltration Heat Loss	1.47E+11	1.74E+11	1.58E+11	1.41E+11	9.30E+10	7.92E+10	1.03E+11	8.95E+11	52%
Ventilation	7.56E+10	9.31E+10	8.21E+10	6.14E+10	3.37E+10	2.87E+10	4.83E+10	4.23E+11	25%
Zone Windows Heat Loss	2.99E+10	3.26E+10	2.71E+10	2.23E+10	1.44E+10	1.43E+10	2.04E+10	2.09E+11	12%
Wall Conduction	2.25E+10	2.49E+10	2.21E+10	1.88E+10	1.14E+10	1.00E+10	1.55E+10	1.25E+11	7%
Roof Conduction	8.44E+09	9.43E+09	8.33E+09	6.85E+09	3.94E+09	3.94E+09	5.75E+09	4.67E+10	3%
Ground Conduction	4.46E+08	5.31E+08	7.48E+08	1.08E+09	1.55E+09	1.72E+09	6.72E+08	6.75E+09	0%

Appendix E – Uncertainty Analysis Results

In this appendix the values utilised in the error analysis will be displayed.

The numbers shown for each form of energy transfer shown below is one iteration out of 100,000. They are shown for illustrative purposes.

Energy Flow	Energy (W)
Conduction Window	11350
Conduction Wall	8100
Solar Gain	12680
Infiltration	38630
Ventilation	25060
Electric (heat)	14000
People	10020
Heating	41950
Qtotal	**-4500**

Below are the mean values which were used to complete the Monte Carlo analysis. These values were taken from the energy model from the peak heating load. This occurred on January 29th at 6:09 PM in the model. The middle column shows the mean value that was chosen for each value based on the energy model results. The right column shows the random value chosen given the standard deviation determined in the energy accounting charts.

Measured Value	Mean Value	XLS Rdm #
	Fluid Values	
Temperature	-	
GSHP	17	17.2
Radiant in Floor Heat	26	26.0
Thermal Storage	60	60.1
Flow Rate	-	
GSHP	11.4	11.7
Radiant in Floor Heat	37.9	42.5
Thermal Storage	20	23.6
	Air Values	
Temperature		

Ventilated Air	24	24.0
Outside Air	-15	-15.1
BIPV	30	29.9
HVAC Air	24	23.9
Flow Rate		
Ventilated Air	20	21.4
BIPV	2	2.7
HVAC Air	48	47.8
Heat Flux Walls (/m^2)		
Heat Flux	7	7.4
Heat Flux Windows		
Heat Flux	11	10.3
Infiltration		
Infiltration Rate	0.3	0.30
Indoor Temperature	24	24.0
Electricity Consumption		
AC Consumed	20000	19900
Solar Gain		
Solar Flux	11.5	11.5
Occupancy Gain		
People	100	90.1
Energy / Person	100	95.2

Below is the uncertainty accounting for each of the sensors that will be utilised in the building. Where applicable, they include the systematic error associated with each measurement as well as the random error of the sensor itself.

Type	Mass Flow Liquid			
Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
Calibration Uncertainty - T1 (Deg C)*	0.45	Normal	2	0.225
Calibration Uncertainty - T2 (Deg C)	0.45	Normal	2	0.225
Resolution - T1 (Deg C)	0.1	Rectangle	1.73	0.058

Resolution - T2 (Deg C)	0.1	Rectangle	1.73	0.058
Combined Uncertainty - T1				*0.232*
Combined Uncertainty - T2				*0.232*
Calibration Uncertainty* - Mdot (LPM)	2	Normal	2	0.500
Resolution - Mdot (LPM)	0.125	Rectangle	1.73	0.072
Combined Uncertainty - Mdot				*1.003*

Type	Mass Flow Air			
Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
Calibration Uncertainty - T1 (Deg C)*	0.055	Normal	2	0.0275
Calibration Uncertainty - T2 (Deg C)*	0.055	Normal	2	0.0275
Resolution - T1 (Deg C)	0.025	Rectangle	1.73	0.0144
Resolution - T2 (Deg C)	0.025	Rectangle	1.73	0.0144
Combined Uncertainty - T1				**0.0311**
Combined Uncertainty - T2				**0.0311**
Calibration Uncertainty* - Mdot (LPM)	2	Normal	2	1
Resolution - Mdot (LPM)	0.25	Rectangle	1.73	0.144
Combined Uncertainty				*1.01*

Type	Heat Flux Wall			
Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
Calibration Uncertainty - Q (Wm2)*	0.25	Normal	2	0.125
Resolution - Q (Wm2)	0.1	Rectangle	1.73	0.0577
Systematic Error - Resistance of Sensor (%)	0.1	Normal	2	0.05
Combined Uncertainty				**0.376**

Type	Heat Flux Window			
Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
Calibration Uncertainty - Q (Wm2)*	0.25	Normal	2	0.125
Resolution - Q (Wm2)	0.01	Rectangle	1.73	0.00577
Systematic Error - Resistance of Sensor (%)	0.15	Normal	2	0.075
Combined Uncertainty				**0.834**

Type	Infiltration			
Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
Infiltration (%)	0.2	Normal	2	0.03
Temperature (Deg C)	0.45	Normal	2	0.225

Type	Electricity			
Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
AC Metering (%)	0.03	Normal	2	300
DC Metering (%)	0.03	Normal	2	0.1

Type	Solar Gain			
Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
Apparatus - Non-Linearity (%)	0.01	Normal	2	0.005
Apparatus - Non-Stability (%)	0.02	Normal	2	0.01
Apparatus - Temperature Dependence (%)	0.02	Normal	2	0.01
Precision	0.008	Rectangle	1.73	0.00462
Combined Uncertainty - Apparatus				0.180
Error - Shading	0.05	Normal	2	0.025
Combined Uncertainty				0.339

Type	Occupants			
Source of Uncertainty	Nominal Value	Probability Distribution	Divisor	Standard Uncertainty
Measurement (%)	0.1	Normal	2	5
Estimate of Energy (%)	0.3	Normal	2	15