TOWARDS MEASURING REAL-TIME OCCUPANT LEVELS TO REDUCE VENTILATION FAN ENERGY CONSUMPTION IN EXISTING INSTITUTIONAL GATHERING SPACES - A FIELD STUDY USING THERMAL SENSORS

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Towards measuring real-time occupant levels to reduce ventilation fan energy consumption in existing institutional gathering spaces - a field study using thermal sensors.

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Abstract

Ventilation systems in buildings have been traditionally designed for the maximum projected number of occupants; while buildings often have fewer occupants than the maximum and in some cases can be unoccupied for extended periods. Changing the rate of outdoor air to reflect changes in the number of occupants in a space is referred to as demand control ventilation (DCV). A field study was performed using thermal sensors to determine the number of occupants using lecture rooms of an institutional building. The occupant data was used to calculate minimum ventilation for the lecture rooms using current ventilation standards from ASHRAE Standard 62.1. It was found that by current standards, the required ventilation is considerably less than the original design ventilation. Based on occupant data and variables specific to the lecture rooms, it was found that the ventilation can be reduced by at least 40% creating a potential for significant energy savings.

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1.0 Introduction

Ventilation systems in buildings have been traditionally designed for the maximum projected number of occupants; while buildings very often have fewer occupants than the maximum and in some cases can be unoccupied for extended periods. In some older buildings, ventilation provides outdoor air at a constant maximum rate in anticipation of the space being filled to capacity. Current ventilation rates are set by ASHRAE standards but buildings that were designed and built prior to ASHRAE standards are likely to have higher ventilation rates than needed. Retrofitting ventilation systems in older buildings to meet current standards can create opportunities for energy savings.

Changing the rate of outdoor air to reflect changes in the number of occupants in a space is referred to as demand control ventilation (DCV) (ASHRAE, 2013). The goal of DCV is to reduce energy by not over ventilating spaces. Measuring the number of occupants in DCV can be done in several methods. The industry standard for occupant measurement in DCV is CO_2 sensors but other sensors and people counter technologies may provide a more reliable way of calculating number of occupants for DCV.

1.1 Objective and Research Questions

The objective of this research project is to determine if DCV in older existing institutional buildings can create substantial energy savings. This project will contribute to developing research into alternate strategies of sensor-based DCV by using a relatively new sensor technology to measure the number of occupants; thermal sensors. A field study measured the number of occupants in the lecture wing of an institutional building that has not been updated to modern standards. Occupant counts were analysed to estimate the potential energy savings of installing DCV system in the lecture rooms.

The research questions for this study are the following;

1. What technologies are available for DCV and have they been tested?
2. Does the original design ventilation reflect the actual number of occupants using the two lecture rooms in the case study building?
3. How much energy savings would DCV provide in the case study building?

1.2 Approach and Scope of Research

The research project focuses on lecture rooms in a multi-use institutional building at the University of Toronto. The ventilation system in the case study lecture rooms is original to when the building was built in 1960, prior to ASHRAE standards. Thermal imaging sensors were used to count people as they entered and exited the rooms to measure the number of occupants using the lecture rooms. The number of occupants in the lecture rooms was also estimated using class schedules and registration enrolment data. The measured and estimated occupant data was used to calculate minimum ventilation requirements using current standards; ASHRAE Standard 62.1. This was compared to the original ventilation system design to estimate the potential energy savings if a sensor-based DCV system was installed.

1.3 MRP Organization

Chapter 1 is an introduction to ventilation in older buildings, DCV, a statement of research questions and scope of the research project. Chapter 2, the literature review, outlines the background for the study including DCV energy savings, indoor air quality (IAQ), and a review of sensors for DCV. The literature review also introduces a pilot project using thermal sensors for DCV. Chapter 3 reviews past and present ASHRAE standards for ventilation. The methodology is outlined in Chapter 4 followed by an explanation of the field experiment in Chapter 5.

The methodology includes:

- A field study using thermal sensors to measure the occupants of two lecture rooms in an institutional case study building.
- Occupant data gathered from the thermal sensors compared to estimated numbers of occupants.
- Minimum required ventilation calculations using the occupant data and current ASHRAE standards.
- Minimum required ventilation of a DCV system compared to the original design ventilation.
- Energy savings is estimated from a percent reduction of ventilation in the case study building.

Chapter 6 will present the results and discussion including calculations of predicted savings. Lastly, future research recommendations and conclusions are made in Chapter 7.

2.0 Literature review

2.1 Demand Control Ventilation

ASHRAE Standard 62.1-2010 *Ventilation for Acceptable Indoor Air Quality* defines demand control ventilation (DCV) as "any means by which the breathing zone outdoor air flow (V_{bz}) can be varied to the occupied space or spaces based on the actual or estimated number of occupants and/or ventilation requirements of the occupied zone" (ASHRAE 62.1 2010). DCV can be as simple as an on-off design in which a room occupancy sensor, timer or light switch can be a signal to HVAC equipment to turn on or off (ASHRAE, 2013). ASHRAE's *Indoor Air Quality Guide* states that the benefits of DCV increase with the level of density, transiency and the cost of energy (ASHRAE, 2013). Spaces such as theatres, auditoriums/public assembly spaces, gyms and classrooms, restaurants, office conference rooms are all common for DCV (ASHRAE, 2013). DCV is most useful in spaces that have varying occupancy during the day (Chao and Hu, 2004).

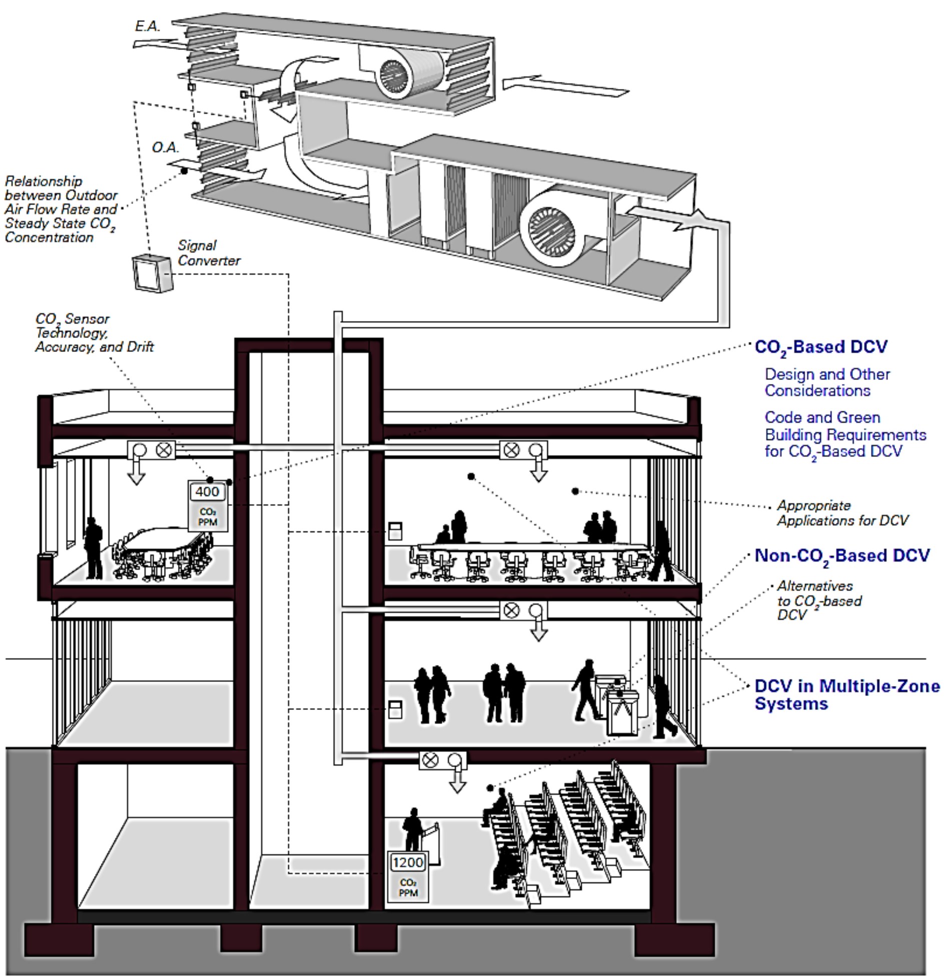


Figure 1. Demand control ventilation design considerations (ASHRAE, 2013).

Figure 1, from ASHRAE *Indoor Air Quality Guide* (2013), shows some of the design considerations for DCV diagrammatically including several items that must be considered when designing a DCV system. It is shown that DCV systems use signal converters take occupant counts and feed them back to a building automation system that controls air handling units (ASHRAE, 2013). Figure 1 shows that in the case of carbon dioxide (CO_2) based DCV, the sensors should be monitored for accuracy and drift. Alternative sensors to CO_2 are also shown in Figure 1, as people counters in the form of turnstiles.

2.2 Demand Control Ventilation Energy Savings

The potential energy savings associated with DCV depends on many variables including the type and age of the building, the HVAC equipment used, the population density and occupancy schedule, and the climate where the building is located, as well as in retrofits of old buildings, the original ventilation design (ASHRAE, 2013). Older buildings perhaps have the greatest potential for energy savings because the original ventilation requirements were designed with older ASHRAE standards or before ASHRAE, when ventilation rates were higher than they are today.

The main goal of DCV is to avoid over-ventilating spaces and therefore reduce energy consumption; while still maintaining an acceptable indoor air quality (ASHRAE, 2013). Providing ventilation to buildings takes energy to run fans and heat and cool the outside air, depending on the season. Buildings with high occupancy and high occupant density, such as sport arenas and auditoriums, have the greatest potential for energy savings, especially in severe climates (Fisk and De Almeida, 1998). This is due to wide fluctuations in number of occupants and energy to heat or cool ventilation air. In addition, buildings that have been designed to supply 100% outside air will have a high energy saving potential versus those that mix outside and recirculated air (Fisk and De Almeida, 1998).

A study by Roth et al. (2005) showed that DCV has a potential to reduce heating and cooling loads by up to 20%. Fisk and De Almeida (1998) found that energy savings associated with reducing ventilation in a particular space varies but can be up to a 50%. Energy savings can be achieved easily through reduction in fan consumption because fan power increases as the cube of the flow rate, a decrease of 20% of air flow means there is a 50% fan energy savings (Fisk and De Almeida, 1998). It has been found that buildings that have excess ventilation entering spaces during periods of low to zero occupancy can require extra energy to heat or cool compared to buildings with DCV (Roth et al., 2005).

Table 1. Cost savings per year of DCV in various building types. Jeannette and Phillips (2006).

Building Type	Spaces DCV Applied	Location	Cost Savings per ft^2 / Year
Elementary Schools (8 schools)	Gyms, large classrooms, media centers, auditoriums, cafeterias	Colorado Springs, CO	$0.09 - $0.33
Middle Schools (6 schools)	Gyms, large classrooms, media centers, auditoriums, cafeterias	Colorado Springs, CO	$0.05 - $0.20
High Schools (4 schools)	Gyms, large classrooms, media centers, auditoriums, cafeterias	Colorado Springs, CO	$0.05 - $0.14
University Building	Large classrooms, offices	Boulder, CO	$0.31
University Building	Large classrooms, offices	Boulder, CO	$0.34
University Building	Large classrooms, offices, lobby, conference room	Denver, CO	$0.23
Ice Rink	Ice rink	Edmonton, Canada	$0.04
University[2]	Lecture halls	Indiana	$0.14 - $0.23
High-rise Office[2]	Open office	Oregon	$0.11
Convention Center[2]	Convention halls	Oregon	$0.10

Jeannette and Phillips (2006) estimated energy and cost savings of DCV using US Department of Energy's DOE-2 building energy simulation tool. Table 1 shows the summary of cost savings for various building types including schools and universities. The report also lists the factors that can affect the energy savings of DCV including occupancy schedule, space heating and cooling loads, ambient temperatures and humidity, HVAC type. Classrooms in University buildings are shown to have a range of $0.14 – $0.34 cost savings per square foot per year **(**Jeannette and Philips, 2006). It is assumed this represents a classroom that was recently constructed. It is anticipated older classrooms, such as those in field study, would have significantly higher cost savings than listed in Table 1.

2.3 Indoor Air Quality

Acceptable IAQ is achieved by providing air to occupied spaces in which the concentration level of contaminants are not harmful and do not cause health or comfort complaints (ASHRAE, 2013). Poor IAQ can affect a building occupant's productivity, comfort and health. In some cases, serious health risks can result from poor IAQ including Legionnaires ' disease, lung cancer and carbon monoxide poisoning (ASHRAE IAQ, 2009). Other impacts include allergies, asthma and symptoms associated with "Sick Building Syndrome" (ASHRAE IAQ, 2009).

The level of CO_2 is one element of IAQ and is related to the quality of the indoor environment. Levels of CO_2 were studied as early as the mid-1800s when recommended levels of CO_2 in a space were at 1000 parts per million (ppm) (Sundell, 2004). In the 1800s and early 1900s, these levels were usually related to body odor rather than actual CO_2 levels (Sundell, 2004). Today's standards have not changed significantly, ASHRAE standard 62.1- 2007 states that CO_2 levels should not be higher than 700 ppm relative to levels of CO_2 measured in outside air (ASHRAE, 2007). CO_2 monitoring is not only used as an indicator of people related contaminants today, it is used as a common method of occupancy measurement for DCV.

Emmerich and Persily (2001) conducted a detailed literature review of the studies available on CO_2 sensors used for demand control ventilation. The technology of CO_2 sensors has changed from 2001; however, the principals outlined in the report are still relevant today. Most notably, Emmerich and Persily concluded that CO_2 sensors cannot account for acceptable indoor air quality because non-occupant pollutants are still present. Non-occupant pollutants can become elevated when DCV systems are used because ventilation is reduced during periods of low occupancy (Emmerich and Persily, 2001). ASHRAE *Indoor Air Quality Guide* (2013) calls for a pre-ventilation of the air after non-occupied times to address non-occupant pollutants.

Chao and Hu's (2004) case study on a lecture theatre in Hong Kong measured indoor pollutants, such as radon, TVOC, formaldehyde and other non-occupant related pollutants and the levels at different times of the day. It was found that radon was the dominant non-occupant related pollutant due to the building materials used in the lecture theatre. The research found that due to the long periods of time when the space was unoccupied and ventilation is lowered, occupants can then be exposed to undesirable indoor air pollutants. Chao and Hu concluded that using CO_2 based demand control ventilation would not address non-occupant-related indoor air pollutants at acceptable levels. It was found that the dominant pollutant should be identified in each case by site measurement and should become the second controlled pollutant. Chao and Hu recommended that a dual-mode demand control ventilation strategy that combined both a sensor for CO_2 and one for the dominant non-occupant related indoor air pollutants could create an acceptable indoor air quality.

2.4 Sensors and Demand Control Ventilation

There are various forms of sensors that can measure the number of occupants in a space; CO_2 sensors are considered the industry standard for DCV, but technologies are emerging to directly count people (ASHRAE, 2013). Calibration and accuracy problems of chemical-sensing technology, such as CO_2 sensors, are a current area of research, and as a result other forms of sensors are becoming available (ASHRAE, 2013). ASHRAE standard 62.1-2010 lists several methods for DCV including CO_2 sensors, population counters, timers, occupancy schedules and occupancy sensors.

DCV relies on occupant data to adjust ventilation. Most applications of DCV rely on sensors to relay information to a building automation system which controls the HVAC equipment. CO_2 sensors can provide a measure human occupancy and activity but has been found to not be a good indicator of IAQ because many contaminant sources are not linked to occupants (Persily, 1997). Another sensor method that is perhaps less common is a thermal sensor that tracks occupancy by counting people at entrances and exits, referred to sometimes as people counters (Fisk and Sullivan, 2009).

2.4.1 CO_2 Sensors

The accuracy of CO_2 sensors have been reviewed in literature and studies have found CO_2 sensors to be unreliable (Shrestha and Maxwell 2010, Fisk et al, 2010). CO_2 sensors have been shown to be unreliable when exposed to pressure, temperature, and humidity and ageing (Shrestha and Maxwell 2010). Questions of accuracy with CO_2 sensors have made it risky for building owners to incorporate DCV into their buildings (Dougan and Damiano, 2004). Another criticism of CO_2 sensors is the timing of the feedback of information. The feedback time on the number of occupants in a space can be delayed from a few minutes to a few hours using CO_2 sensors because the level of CO_2 will increase after occupants have entered a space and had time to expel CO_2 (Fisk et al, 2010).

The CO_2 sensor location has been found to be crucial to the accuracy of the occupant count (Chao and Hu, 2004). The best location for reading CO_2 would be in the breathing zone (Chao and Hu, 2004). This is not practical in most cases. For example, a classroom could not have sensors located in the breathing zone as it would obstruct the activities of the people in the room (Chao and Hu, 2004). In practice, CO_2 sensors are commonly found in the return duct of the space. In a case study conducted by Chao and Hu in 2004 of a lecture room in a Hong Kong University, it was found that the return air was also a by-pass for fresh air due to short circuiting, and therefore the return air duct location did not give an accurate reading of CO_2 in the room. To compensate for the mixing of fresh air in the Chao and Hu case study, there were correlations completed to adjust for the incorrect levels of CO_2 being measured. This example shows the idiosyncrasies of each individual DCV design and that DCV cannot be a one size fits all approach.

Fisk et al. (2010) authored a report for the Lawrence Berkeley National Laboratory and the California Energy Commission on the use of CO_2 sensors for demand control ventilation in commercial buildings. The results were based on a combined study with a total of 208 sensors in 34 buildings in California. The study included using bags of CO_2 calibration gases to evaluate sensor performance. Using 6 brands and multiple models of CO_2 sensors, errors were found in measured levels in ppm where average and median values of percent error were 68% and 43%, respectively. The errors were found to be problems with the sensors themselves and varied between manufacturers. Fisk et al. (2010) believed the sample size in the study was small but concluded that the CO_2 sensors were not sufficiently accurate to measure occupants for DCV. Fisk concluded when there is poor sensor accuracy; DCV systems would not save energy.

Shrestha and Maxwell (2010) performed a lengthy four part study to test and evaluate CO_2 sensors for HVAC applications. 15 models with a total of 45 sensors were studied for a period of one year. CO_2 sensors were placed in test chambers and tested for accuracy to +/- 5ppm. Shrestha and Maxwell tested performance, humidity, temperature, pressure, and ageing. It was found that performance varied among the sensors and in many cases did not meet the stated manufacturer's accuracy range. It was found first that sensor performance varied among manufacturers within the same conditions (2009 part 1) and some performance varied between sensors of the same model (2010 part 2). A wide variation was found when humidity and temperature differences were applied in 3 sensor models. Temperature affected the sensors at a maximum of 10ppm per 1.8° F (2010 part 3). Pressure also affected the sensor performance and it was found that fluctuating barometric pressures would affect the accuracy of the sensors (2010 part 3). The ageing test was conducted by isolating the sensors and exposing them to high CO_2 concentrations for 3 days per week and 8-12 hours a day. It was found that some models showed nominal ageing but one model showed significant errors of up to -376ppm (2010 part 4).

Shrestha and Maxwell (2010) noted in their research that sensor models require calibration every 3.5 years. Calibration involves calibration gas (a known CO_2 level) passing over the sensor's optical sensing element (Shrestha and Maxwell, 2010). Accurate calibration also requires knowing the temperature and pressure of the gas at the optical sensing element (Shrestha and Maxwell, 2010). Fisk et al. (2010) suggested that the lack of maintenance and calibration could contribute to accuracy errors. It was found in the Fisk et al. (2010) study that facility managers did not to calibrate the sensors after the initial installation.

Dougan and Damiano (2004) discussed the risks associated with the CO_2 DCV approach relative to the benefits of energy savings. Dougan and Damiano list that CO_2 sensors have 13 different technology specific sensitivities, and other considerations which can lead to errors. The sensitivities include the following:

- Drift;
- Overall accuracy;
- Temperature effects;
- Water vapor;
- Dust Buildup;
- Age of light source;
- Frequency of calibration
- Mechanical vibration;
- Electrical noise;
- Sensor location in the space;
- Number of sensors required;
- Method of averaging multiple sensors; and
- Compounded error rates from multiple sensors.

It was concluded by Dougan and Damiano that owners can be at risk when installing CO_2 based DVC systems in their buildings because of assumptions that need to be made in CO_2-based DCV.

2.4.2 Thermal Sensors

There are few studies on alternate sensors to CO_2 for DCV. One study was found by Fisk and Sullivan (2009) for the Lawrence Berkeley National Laboratory and the California Energy Commission. Fisk and Sullivan carried out a pilot study of optical people counting using thermal sensors for DCV. Thermal sensors were installed in 3 entrance locations; a lab, conference room and office building entrance. It was found that the errors for this type of sensor technology were less than 10%. It was found that the errors can be high, however, if there are entry areas where people stand for periods of time, people carrying cups of coffee, or wearing a heavy winter coat. No errors were found with two people standing side by side or closely following each other while walking through the sensor area. It was concluded that although this was a small study, people counters should be explored further as a DCV method.

2.5 Pilot Study at University of Toronto OISE

University of Toronto, Facilities and Services has piloted a project to introduce DCV using thermal sensors in the Ontario Institute for Studies in Education (OISE) building, located at 262 Bloor Street West, Toronto. The DCV system used thermal sensors to count the number of occupants entering the building, as well as, the number occupants on each floor (Walker, 2013). A building automation system receives the occupant data and controls air handling units (AHUs) in various zones of the building. Existing AHUs were retrofitted with variable frequency drives (VFDs) to control fan speed (Walker, 2013). As well, the AHU's have be deactivated for un-occupied periods such as night times. The system was designed to meet and exceed ASHRAE 62.1 standard (Walker, 2013).

In preparation for the pilot project at OISE, a number of thermal sensors were installed in the building to estimate the number of occupants. It was found from the data collected that the actual number of occupants using the building was 85% less than the design occupancy from 1969. The pilot project found that the following components of the space must be monitored as they affect the DCV system; pressure in the space, static pressure, airflow and CO_2 levels (Walker, 2013). It was estimated that ventilation could be reduced by 70% of the original design and still meet and exceed minimum standards on DCV set by ASHRAE 62.1 (Walker, 2013). Information provided by Facilities and Services reported that CO_2 and pressure sensors were also installed as a secondary control parameters (Walker, 2013).

Although the pilot project at OSIE is in preliminary stages, the system is running as expected according to University of Toronto's Facilities and Services group. The investment was relatively large; including retrofitting AHUs with VFDs. The expected payback period for the investment is 2 years (Walker, 2013).

2.6 Summary of Literature Review

DCV systems are proven to save energy but the amount of energy saved depends on many variables. Retrofit of older buildings with original, outdated ventilation systems to DCV systems could provide a significant energy savings because original ventilation systems were designed with much higher ventilation rates than current standards. Sensors technology is a key component of DCV, but accuracy problems with CO_2 sensors may have caused slow growth of DCV in the building industry. Unreliable sensors may cause building owners to feel there is too great a risk of poor IAQ to invest in DCV despite the proven energy savings. IAQ can be at risk when ventilation is turned down or off and cannot be measured with CO_2 alone. Monitoring for occupant related pollutants and non-occupant pollutants should be part of a DCV system.

New technologies are developing but very few studies have been done on alternate sensors used to measure occupants for DCV. Thermal sensors are a new emerging technology and may provide an easier and more reliable way to measure occupants, however, more research should be done to verify the accuracy of the sensors.

3.0 Demand Control Ventilation Standards and Guidelines

In order to address concerns about indoor air quality (IAQ), ASHRAE standard 62.1 -2004 introduced a change to DCV and how to determine the ventilation rate (breathing-zone air flow V_{bz}) (Lui et. a., 2012). Recent versions of ASHRAE 62.1 calculate the amount of required ventilation based on the population of people within a zone but still maintain minimum ventilation related to the floor area of the zone (Lui et. al, 2012). Prior to the 2004 standard, ASHRAE 62.1-1989 thru-2001 required minimum ventilation to be calculated either the number of occupants in the zone or the floor area of the zone (Lui et. al, 2012).

Further changes to the latest version, ASHRAE 62.1 – 2010, allows for unoccupied zones to have the ventilation turned off when there are no occupants present (Bohanon 2011). For example, in a classroom setting, ASHRAE standards currently allow DCV to be designed to adjust relative to actual number of occupants, turn down to a minimum between scheduled occupancy (between class times or a lunch or dinner break) and turn completely off overnight. However, ventilation must turn back on prior to the start of anticipated occupancy for a minimum 3 ACH (ASHRAE, 2013).

The most recent trend towards energy savings and sustainability in buildings has developed new standards that encourage DCV. LEED, Leadership for Energy and Environmental Design, includes CO_2 monitoring as a method to obtain certain credits (Lawrence, 2004). One point is available for CO_2 monitoring and DCV can contribute to two more points depending on the level of energy savings (Lawrence, 2004). Title 24, California's Energy Efficiency Standards, requires CO_2-based DCV for single-zone high-occupancy areas (greater or equal to $3.7m^2$/person) although there are some exceptions (ASHRAE, 2013).

ASHRAE's 189/1-2009 *Standard for the Design of High-Performance Green Buildings*, a voluntary standard, requires DCV for "densely occupied spaces" defined as a design occupant density greater than or equal to 27 people per 100 m^2 (ASHRAE, 2013). ASHRAE's 90.1-2007 *Energy Standard for Buildings Except Low-Rise Residential Buildings*, a voluntary standard, requires DCV for spaces larger than 46 m^2 and a design occupancy for ventilation of more than 43 people per 100 m^2 (Bohanon 2011). This standard also requires DCV for spaces served by systems with a design outdoor air capacity greater than 142 L/s (3000 CFM) or with an air-side economizer or automatic modulation control of the outdoor air damper (ASHRAE, 2013).

ASHRAE 62.1-1989 thru-2001 used, Equations 1 and 2 as the two methods for calculating minimum ventilation rates based on the number of occupants or the floor area of the zone (Lui et al, 2012).

$$V_{bz} = R_p \, x \, P_z \qquad [1]$$

or

$$V_{bz} = R_a \, x \, A_z \qquad [2]$$

Where,

V_{bz} = outdoor air ventilation rate
R_p = required outdoor airflow rate per person, cfm/person
P_z = zone population, number of people
R_a = required outdoor airflow rate per unit area, cfm/ft^2
A_z = zone floor area, ft^2

ASHRAE standard 62.1 -2004 and recent versions combine the two ventilation rates and use the following formula to calculate the ventilation rate (Lui et al, 2012).

$$V_{bz} = (R_p \, x \, P_z) + (R_a \, x \, A_z) \qquad [3]$$

Where,

V_{bz} =outdoor air ventilation rate
R_p = required outdoor airflow rate per person, cfm/person
P_z = zone population, number of people
R_a = required outdoor airflow rate per unit area, cfm/ft^2
A_z = zone floor area, ft^2

This change to ASHRAE is meant to address the non-occupant pollutants or building related sources, and not base ventilation the occupancy alone (Lui et al, 2012). The difference, for example, in a classroom scenario of 100 m^2 and 65 people; the calculated ventilation rate from ASHRAE 62.1-2004 would be 277 L/s (3.8L/s per person x 65 people + 0.3 L/s*m^2 x 100 m^2) compared to the ASHRAE 62.1-1989 thru-2001 which would have required 455 L/s (7 L/s x 65 people) for the same space and occupancy. The two equations are shown for varying sizes of classrooms, below in Table 2.

Table 2. Comparison of ASHRAE 62.1 standards used to calculate minimum ventilation rates.

	ASHRAE 62.1-1989 thru-2001 Vbz = (Rp x Pz)			ASHRAE 62.1 – 2004 Vbz = (Rp x Pz) +(Ra x Az)				
	Rp (L/s / person)	Pz (number of people)	Vbz (required L/s)	Rp (L/s / person)	Pz (number of people)	Ra (L/s*m^2)	Az floor area (m^2)	Vbz (required L/s)
Example classroom 150 m^2, 100 people	7	100	700	3.8	100	0.3	150	425
Example classroom 100 m^2, 65 people	7	65	455	3.8	65	0.3	100	277
Example classroom 50 m^2, 40 people	7	40	280	3.8	40	0.3	50	167

4.0 Methodology

A building at the University of Toronto is used as a field study to measure the number of occupants in two lecture rooms. Measurements are taken in the lecture wing of Ramsay Wright Laboratories building, located at 25 Harbord Street, Toronto. The lecture wing was chosen because it has a separate ventilation system serving only the area of the two lecture rooms, Room 110 and Room 117. The compartmentalization of this part of the building makes it an appropriate case study to look at reduced ventilation and potential energy savings. The number of occupants in the space fluctuates during the day because it is used for scheduled classes. The lecture rooms were also chosen based on literature that finds that spaces that are densely occupied and have varying occupancies throughout the day can provide the most energy savings (ASHRAE, 2013). Figure 2 shows the first floor plan of the Ramsay Wright building with the lecture wing highlighted.

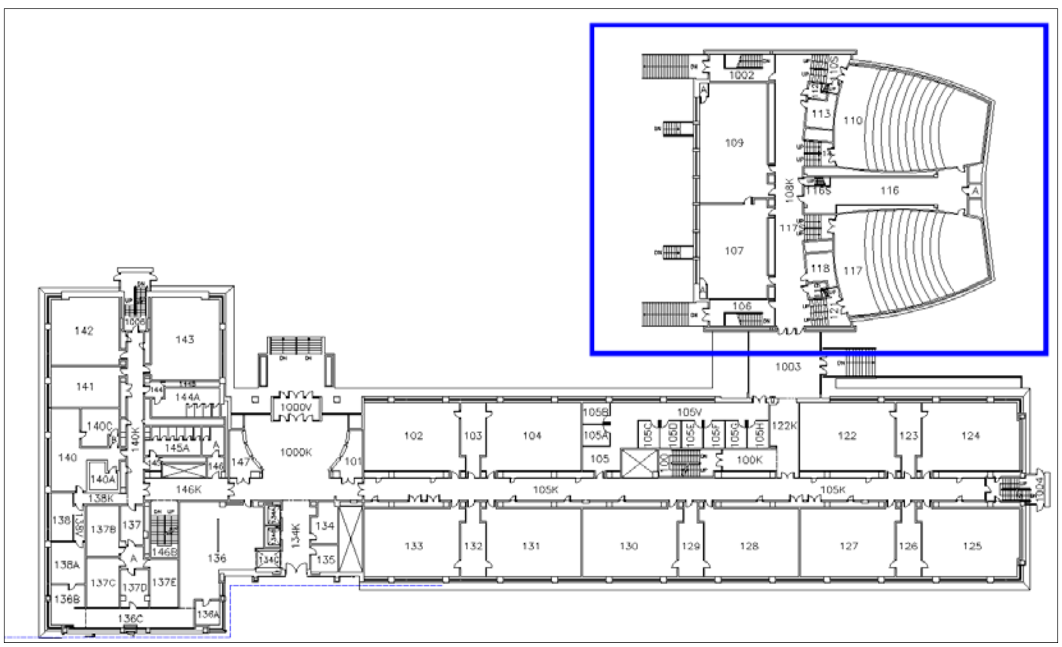


Figure 2. First Floor plan of Ramsay Wright Laboratories highlighting the Lecture wing.

4.1 Number of Occupants

The methods used to find the number of occupants is two-fold and two sets of data; **measured** number of occupants and **estimated** number of occupants are compared. First, thermal sensors are used to count people as they enter and exit the two lecture rooms. In collaboration with the University of Toronto's Facilities and Services Department, four thermal sensors were installed, one at each entrance to the lecture rooms. The thermal sensors collected data continuously for a one week period from November 25 to 29, 2013. This is considered a good time of year to collect data because it is near the end of term classes. Class attendance in expected to be high at the end of a semester because students are preparing for exams (University of Toronto, 2013).

The thermal sensors used for data in this project were Traf-Sys™ thermal imaging sensors. The sensors are mounted overhead and measure bi-directional traffic by detecting heat emitted by people passing through the area (Traf-Sys, 2013). The sensors detect infrared naturally given off by people. Infrared is a type of radiation with a wavelength that cannot be seen but can be detected as heat (Irisys, 2013). Thermal sensor units contain imaging optics, the sensor, signal processing and interfacing electronics within the housing of the sensor (Irisys, 2013). The thermal sensors detect the direction of travel within the view of measurement.

The sensors used for the measured occupants in this study were connected to a data controller that records the data every 10 to 30 seconds (Traf-Sys, 2013). Calibration is done at installation so that counts are recorded as "in" or "out". The occupant count data is downloaded to software by connecting a laptop to the controller, the calculation and reporting of the occupant counts were done by Feedback Solutions (Walker, 2013) and provided for this study.

Photo 1 represents an image produced by the thermal sensors. The photo is de-noted to show each individual counted and direction of travel. The thermal sensors record in and out counts and an algorithm is used in the software system to create totals in 30 minute blocks of time, as well as running totals. The image from the thermal sensor is not a clear image; a camera image is shown for comparison.

Photo 1. Image produced by thermal sensors. (Traf-Sys, 2013).

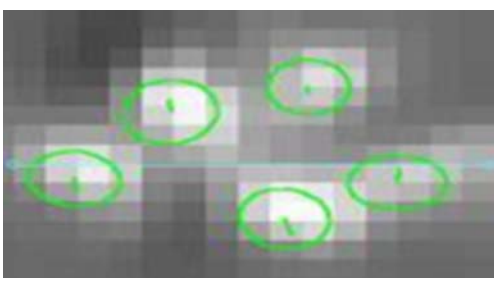


Photo 2. Camera image for comparison (Traf-Sys, 2013).

The second method of occupant data is an estimated number of occupants; taken from the schedule of classes and enrolment data for the two lecture rooms. Classes are booked in the two lecture rooms between 8am and 9pm weekdays. Class schedule information was provided by the University of Toronto's Registrar's office and is the accurate enrolment data representing student numbers after the drop or add dates for the Fall 2013 semester. The estimated number of occupants represents the maximum number of students in the space based on 100% class attendance.

4.2 Ventilation Calculations

The minimum ventilation requirements (litres per second or L/s) for the lecture rooms is calculated using ASHRAE standard 62.1 ventilation rate procedure, Equation 3, for each hour of the day during the test period. Both the measured number of occupants and the estimated number of occupants are used for the calculations and the values are compared. Table 3, taken from ASHRAE 62.1, shows the minimum ventilation rates in breathing zone for a lecture hall with fixed seats (R_p) is 3.8 L/s (7.5 CFM) per person, and the area outdoor air rate (R_a) as 0.3 L/s m^2 (0.06 CFM/ft^2). These two values were used to calculate the minimum ventilation required using occupant data collected and the floor area of the lecture rooms at 168 square metres (1811 square feet) each.

Table 3. ASHRAE minimum ventilation rates in breathing zone (ASHRAE, 2007).

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Correctional Facilities									
Cell	5	2.5	0.12	0.6		25	10	4.9	2
Dayroom	5	2.5	0.06	0.3		30	7	3.5	1
Guard stations	5	2.5	0.06	0.3		15	9	4.5	1
Booking/waiting	7.5	3.8	0.06	0.3		50	9	4.4	2
Educational Facilities									
Daycare (through age 4)	10	5	0.18	0.9		25	17	8.6	2
Daycare sickroom	10	5	0.18	0.9		25	17	8.6	3
Classrooms (ages 5–8)	10	5	0.12	0.6		25	15	7.4	1
Classrooms (age 9 plus)	10	5	0.12	0.6		35	13	6.7	1
Lecture classroom	7.5	3.8	0.06	0.3		65	8	4.3	1
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150	8	4.0	1
Art classroom	10	5	0.18	0.9		20	19	9.5	2
Science laboratories	10	5	0.18	0.9		25	17	8.6	2
University/college laboratories	10	5	0.18	0.9		25	17	8.6	2
Wood/metal shop	10	5	0.18	0.9		20	19	9.5	2
Computer lab	10	5	0.12	0.6		25	15	7.4	1
Media center	10	5	0.12	0.6	A	25	15	7.4	1
Music/theater/dance	10	5	0.06	0.3		35	12	5.9	1
Multi-use assembly	7.5	3.8	0.06	0.3		100	8	4.1	1

Table 4 and Figure 3 below show a range of occupancies and calculated ventilation rate for one lecture room in the case study. This method is used to show how the minimum required ventilation increases as occupant numbers increase in the lecture rooms of the case study building.

Table 4. Minimum required ventilation for case study lecture room and various occupant values using Equation 3.

	ASHRAE 62.1 Vbz = (Rp x Pz) +(Ra x Az)				
	Rp (L/s / person)	Pz (number of people)	Ra (L/s*m^2)	Az floor area (m^2)	Vbz (required L/s)
Case study room 168 m^2, 0 people	3.8	0	0.3	168	50
Case study room 168 m^2, 40 people	3.8	40	0.3	168	202
Case study room 168 m^2, 100 people	3.8	100	0.3	168	430
Case study room 168 m^2, 160 people	3.8	160	0.3	168	658

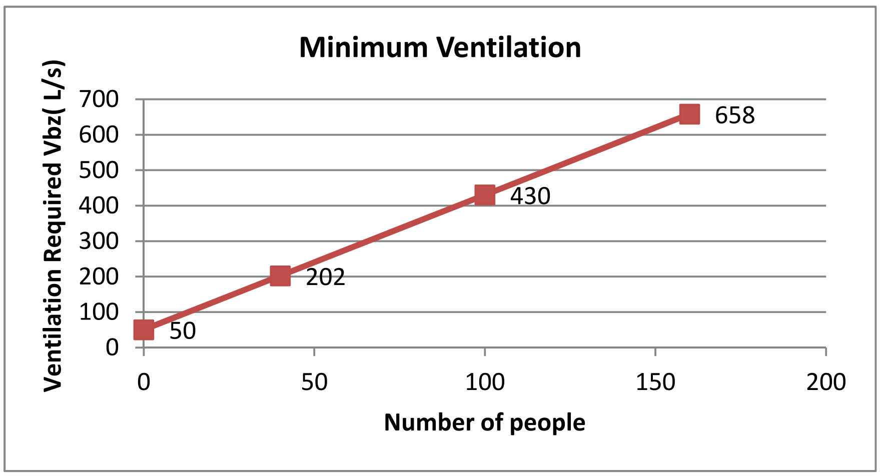


Figure 3. Line graph showing minimum required ventilation relative to increasing occupant values.

4.3 Energy reduction

To estimate an energy reduction in fan consumption, the minimum required ventilation based on number of occupants in the lecture rooms is compared to the original design ventilation. The reduction of ventilation based on occupant numbers reflects the ventilation if a DCV system were applied to the case study lecture rooms. An estimation of the reduction in ventilation will be used to calculate a range of energy savings for the case study lecture rooms; it is calculated in kWh.

There are many factors that affect the amount of energy that can be saved, including the design of the space itself and the type of mechanical equipment. Pressure, calibration, pre-ACH, proper mixing, and continuous measurement all have to be addressed once DCV is implemented in any building (ASHRAE, 2013). Although the air handling unit in the case study provides heating and cooling to the space, this study focuses on fan consumption as a measure of energy savings. The breadth of this study does not include calculations for the reduction in heating and cooling loads.

Calculations can be made to estimate fan energy consumption (kWh) savings over one year. The calculations take into account several variables associated with the AHU unit including fan horsepower (HP), motor efficiency (%), load factor of the fan (%), as well as the number of hours that the AHU is running. A list of variables that are used to calculate energy savings is presented in Table 7. Motor efficiency is the ratio between power transferred to the air stream and power delivered by the motor to the fan and the load factor is the ratio of the load that a piece of equipment actually draws when it is in operation to the load it could draw (Bleier, 1988).

Table 5. List of variables used to calculate fan consumption of existing system.

List of Variables
Existing Fan Volume, L/s
Existing Total Fan Power, HP
Existing Motor Efficiency, %
Load Factor %
Hours of operation

The following equation was used to calculate the savings in electricity if there was a percent reduction in ventilation for the air handling unit (Walker, 2013). The conversion factor 0.746 is used for HP to kW (Bleier, 1988).

$$Fan\ Consumption\ (kWh) = (Hp\ x\ 0.746\ x\ hours)/(Motor\ efficiency\ x\ Load\ Factor) \quad [4]$$

Equation 4 is used to calculate the existing fan consumption energy, as well as the fan consumption from a reduced ventilation, or DCV system, in the lecture rooms. The hours of operation for the existing system and a proposed DCV system are used in the calculations. The reduced ventilation (DCV system) hours are estimated using the academic schedule for University of Toronto and represent days when classes are held throughout the year. The overall energy savings from reduced ventilation subtracts the fan consumption from a ventilation system using DCV from the existing fan consumption; as shown in the following equation (Walker, 2013).

$$Energy\ savings\ (kWh) = Existing\ Fan\ Consumption\ (kWh) - Reduced\ Fan\ Consumption\ (kWh) \quad [5]$$

4.4 Methodology Summary

The number of occupants in the lecture room over a one week period are analysed to compare the actual number of occupants to the maximum number the space can hold. The two sets of occupant data is compared; **measured** number of occupants and **estimated** number of occupants. The minimum ventilation requirements are determined using current ASHRAE 62.1 standards and the occupant counts. The minimum required ventilation of today's standards is compared to the original design ventilation and the difference is used to calculate an energy savings. Because required minimum ventilation in DCV would fluctuate, an average minimum required ventilation is calculated to compare to the original design ventilation. Based on the occupant analysis, the scheduled use of the lecture rooms and other variables that affect the amount of ventilation needed, a safe percent reduction of ventilation is estimated.

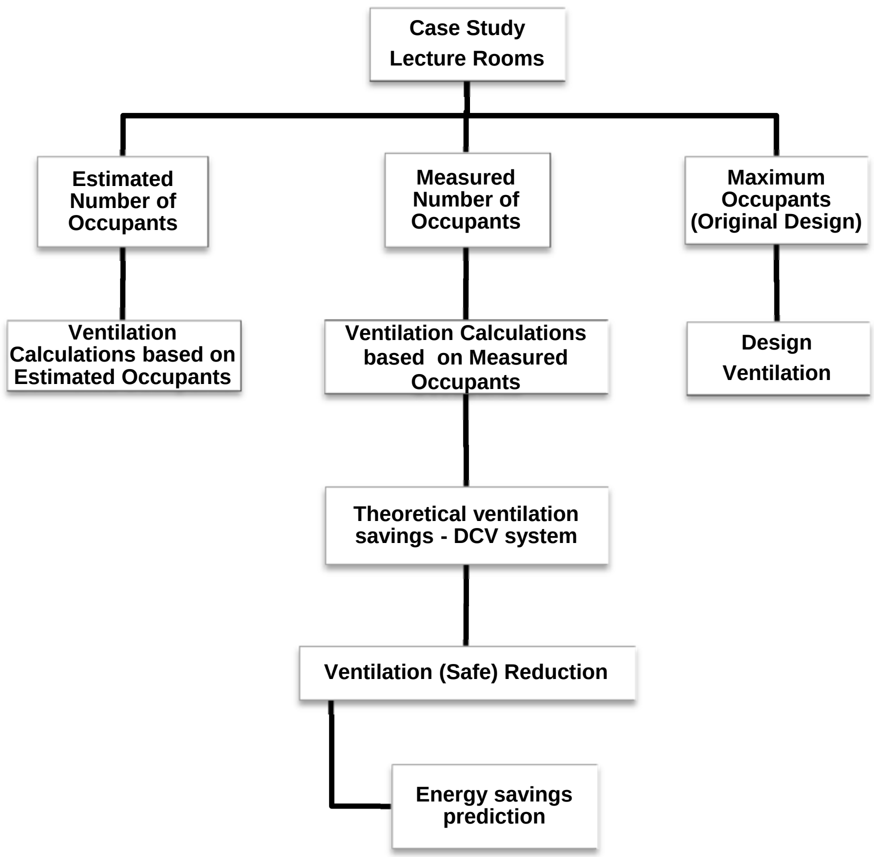


Figure 4. Methodology Flow Chart.

5.0 Field Experiment Set-up and Case-Study Building Information

5.1 Case-Study Building

The field experiment was carried out in the lecture wing of Ramsay Wright Laboratories building. Ramsay Wright Laboratories is 6-storey building that was built in 1960 and is 25,000 square metres (269,100 gross sq. ft). The breakdown of space use is shown in Table 3 (University of Toronto, 2013). The Ramsay Wright Laboratories Building houses research and teaching laboratories, as well as, offices and lecture rooms. The ventilation system for the lecture wing is served by one air handling unit, AHU11, which is original to when the building was built (Walker, 2013). The lecture wing includes 2 large identical tiered classrooms at 168 m^2 each with 160 seats in each.

Table 6. Case study building: Ramsay Wright Laboratories Building space use by category (University of Toronto, 2013).

Ramsay Wright Laboratories	
Category Name	**Net Area(sqm)**
Classrooms	832
Teaching Labs	3229
Research Labs	6723
Office/Study Space	2021
Other (Plant maintenance, Non-assignable areas)	7839
Total Net Square Metres	20643

The following was known about the mechanical equipment for the lecture wing (Walker, 2013):

• This area is served by AHU-11 located on the mezzanine above the first floor lecture theatres.

• The air handling unit is a constant volume providing cooling and heating, with 100% outdoor air for the lecture theatres.

• AHU-11 does not currently have the ability to be turned down or shut off during low or no occupancy periods.

• The balance of the first floor is served by AHU-6 and AHU-12 (as seen in Figure 4).

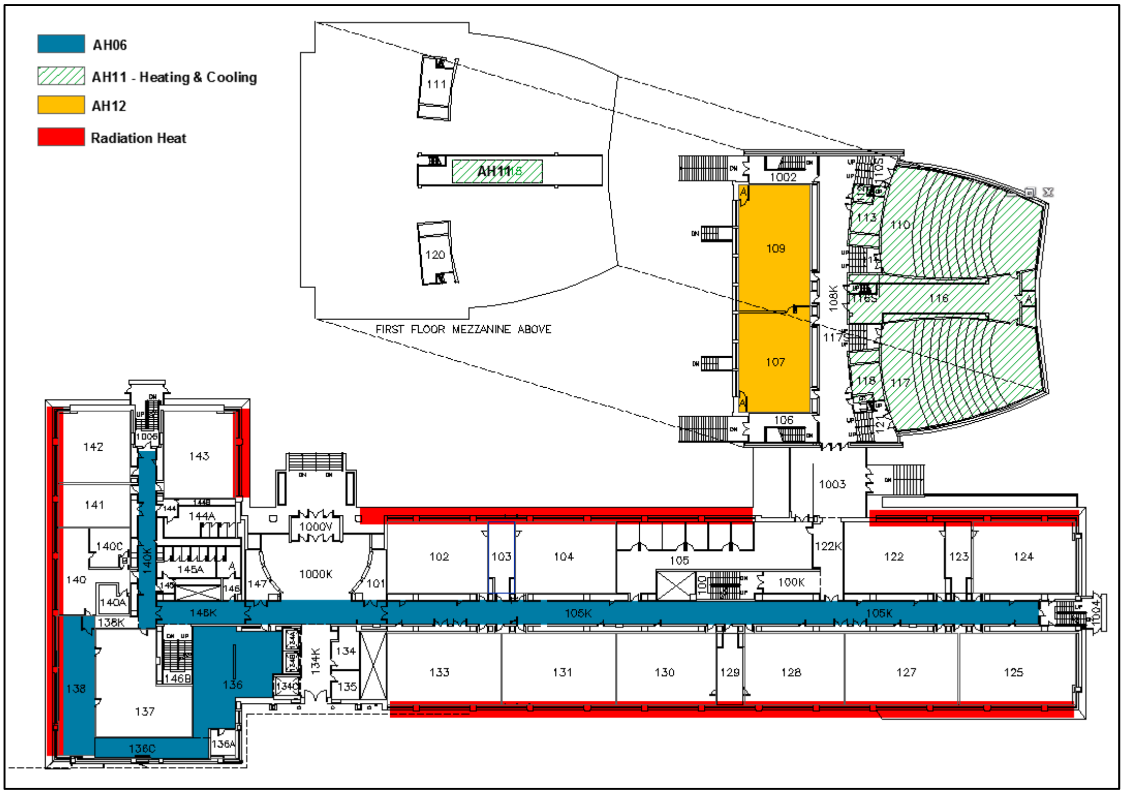


Figure 5. Ventilation systems diagram for the first floor of the case study building, Ramsay Wright Laboratories (University of Toronto, 2013).

Energy data provided by Facilities and Services department in Table 7 below shows the whole building monthly electricity data. The energy use per square metre is calculated to be 365 kWh/m^2.

Table 7. 2012-2013 Energy data for Ramsay Wright Laboratories building (Walker, 2013)

Ramsay Wright Laboratories		
Electricity Utility Data		
2012-2013	kW	kWh
April	1103	732900
May	1378	823200
June	1407	837900
July	1497	861000
August	1428	995400
September	1386	701400
October	1302	709800
November	1113	825300
December	987	472500
January	1019	674100
February	972	554400
March	993	468300
Total		8656200

5.2 Original Design Ventilation

The original design ventilation for the lecture rooms in the case study building was calculated per room. The design ventilation for the lecture wing at Ramsay Wright building was assumed to be that which would have been the standard in the late 1950s and early 1960s, prior to ASHRAE standards. The ventilation rate that would have been used in the design of the building would have been 14 L/s (30 CFM) per person; a rule of thumb for classrooms at the time (Baker, 2012). Applied to maximum occupancy of 160 people in each lecture room the design ventilation was calculated to be 2265 L/s (4800 CFM) per room. This value gives a total outdoor air rate for the lecture wing of 4530 L/s (9600 CFM). In personal correspondence with Facilities and Services, this was believed to be an accurate and conservative assumption of the original design ventilation. In addition, the existing air handler that serves the space which was confirmed to be a unit sized for 5660 L/s (12,000 CFM) (Walker, 2013). The air handling unit used for the lecture wing is not currently controlled by any central system or by a building automation system. The ventilation for the lecture rooms is therefore running 24 hours a day and 7 days a week regardless of the number of occupants in the space.

5.3 Thermal Sensors

One sensor was placed at each of the two entrances to lecture Room 110 and 117, as shown in Figure 4. There are no other exits entrances to the rooms that are used by students or professors. The floor plan (Figure 5) shows an alternate exit at the east end of the rooms, exiting through room 116 but this is an emergency exit only and is not used regularly.

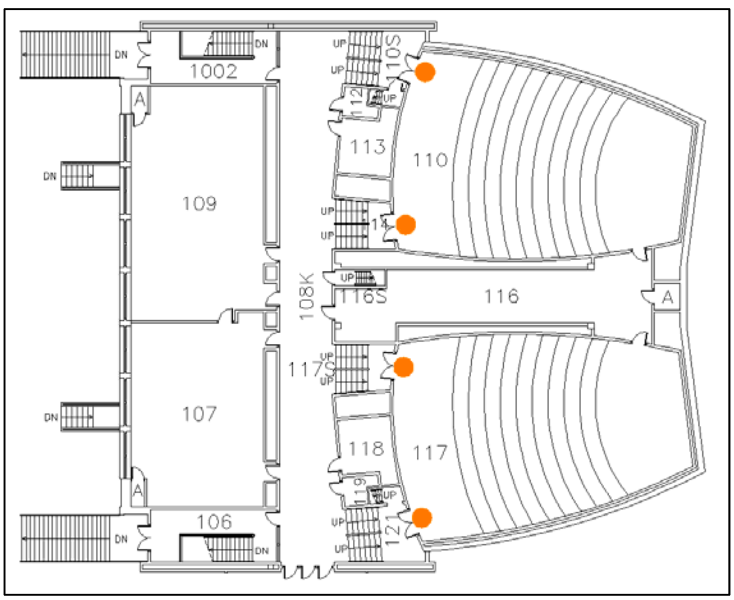
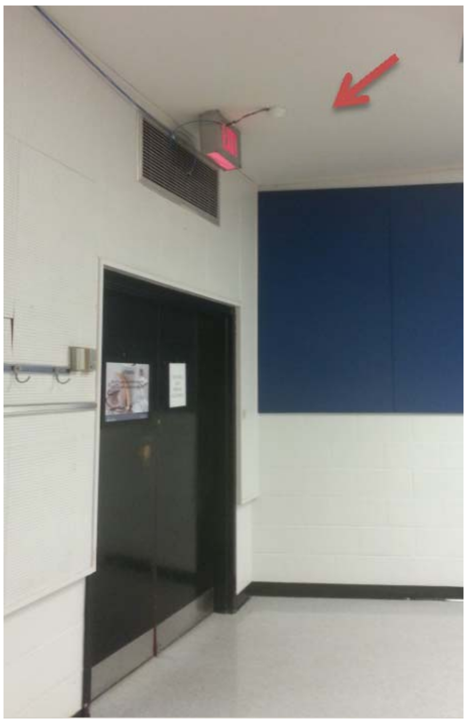


Figure 6. Floor plan showing the case study building's lecture wing and sensor locations.

The strategy for sensor locations was contemplated based on the requirements of the sensors. The entrance to the lecture rooms have a number of stairs which were observed to have students linger and sit while waiting for classes to start and end. For this reason, the location outside the lecture theatre was not suitable for thermal sensors to collect data. Also the ceiling height was not optimal outside the rooms. Inside the entrance, however, the area was found to be unobstructed, did not have students linger and had a ceiling height optimal for the sensors (at 11’-0”). Photo 3 shows the installation of the temporary sensors in the lecture rooms.

Photo 3. Installation of thermal sensors in lecture room 117.



6.0 Results and Discussion

6.1 Comparison of Measured and Estimated Number of Occupants

Figures 7a and 7b show an hourly comparison of the data collected for estimated number of occupants and measured number of occupants for rooms 110 and 117 in the case study building. The data was collected over 1 week period (Monday to Friday) from November 25-29. Occupant numbers from the thermal sensors was reported in 30 minutes intervals. The values shown in Figure 7a and 7b are the higher of two values shown on each hour block from the data. The higher of the two values was taken to reflect the maximum occupancy during one hour block class time and to avoid times of the class as students may come in late or leave early.

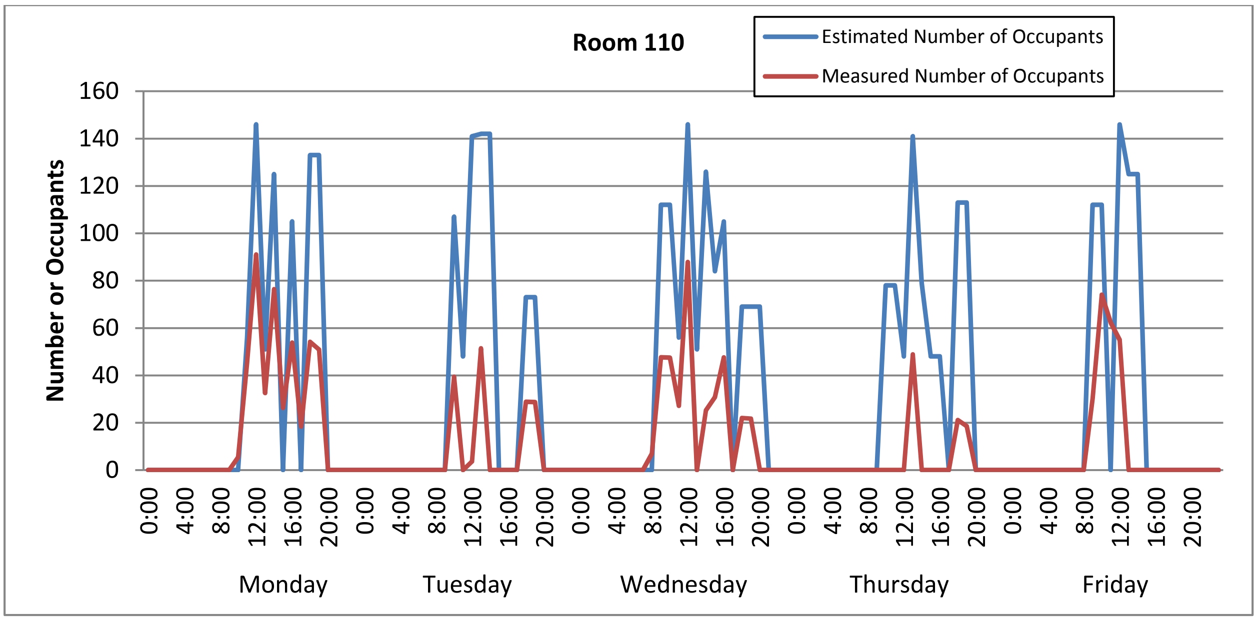


Figure 7a. Estimated number of occupants compared to measured number of occupants for Room 110 from November 25 to November 29, 2013.

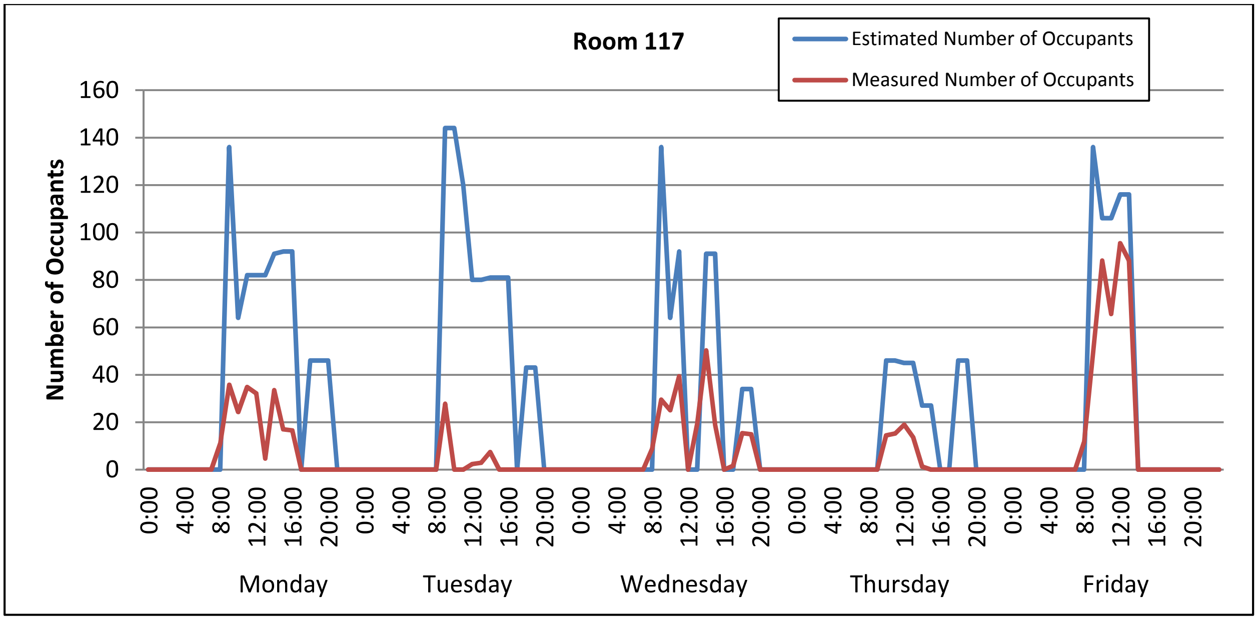


Figure 7b. Estimated number of occupants compared to measured number of occupants for Room 117 from November 25 to November 29, 2013.

Figures 7a and 7b show that the measured number of occupants from thermal sensors follows the pre-booked schedule. A comparison of the measured and estimated number of occupants show what was expected; the measured data for each timeslot is less than the estimated. Measured occupants was expected to be less than the estimated number of occupants because estimated occupants represents the maximum number of occupants in the space and class attendance at 100%. Class attendance was expected to be less than 100%

Table 8a. Summary comparing the estimated and measured number of occupants minimum and maximum values in Room 110 and 117 over November 25-29, 2013.

Occupancy	Maximum Room 110	Maximum Room 117	Minimum Room 110	Minimum Room 117
Estimated	144	146	27	48
Measured	95.5	91	1.3	3.7

Table 8b. Summary comparing the estimated and measured number of occupants average values in Room 110 and 117 over November 25-29, 2013.

Occupancy	Average Room 110	Average Room 117	Average Overall	% difference Estimated vs. Measured
Estimated	98.5	78.2	88.1	62.0%
Measured	40.0	27.5	33.6	

Table 8a and 8b show summary comparisons of the estimated and measured number of occupants. The estimated numbers of occupants show the highest enrolled classes at 144 and 146 people. From the measured data it was found that the most occupants at one time in Room 110 was 96 people and 91 people in Room 117. The minimum measured number of occupants was 1.3 and 3.7 for rooms 110 and 117, respectively. The average hourly number of occupants from the measured data was 33.6, as compared to 88.1 from the estimated number of occupants. The comparison shows, as expected, the average measured number of occupants is lower than the average estimated number of occupants; at a value of 62%.

The measured numbers of occupants show a small number of occupants between classes. For example, prior to a scheduled class on Monday at 11am, at 10am, there is a count of 6 occupants. There are small numbers of occupants present at some times between, before and after classes when no class was scheduled. This occupancy is assumed to be students early for class, or using the room for meetings after class.

6.2 Thermal Sensor Accuracy

Table 9 shows the accuracy of the thermal sensors based on the total number of people in and out of the space on each day of data collection. The accuracy each day ranges from 94% to 100%. 100% accuracy represents an equal count of people in and out of the room during the day. The 94% represents a miscount of 18 people in one room during the one day; Nov 25 in Room 117.

Table 9. Lecture room in/out counts by thermal sensors to show a measure of accuracy.

Date	Lecture Room 110			Lecture Room 117		
	In	Out	Accuracy	In	Out	Accuracy
25/11/2013	441	454	97%	279	297	94%
26/11/2013	256	261	98%	331	343	97%
27/11/2013	435	456	95%	213	213	100%
28/11/2013	296	308	96%	107	112	96%
29/11/2013	171	172	99%	262	272	96%
	1599	**1651**	**97%**	**1192**	**1237**	**96%**

In addition to comparing the total number of occupants in and out of the rooms, site observations were performed by taking a manual count of people in the space. The site observation took place during two morning classes in the rooms in the 9am and 10am slot. A comparison of the counts in Table 10 show that the reported thermal sensor data found that the numbers matched the manual counts within -/+ 6 people, an accuracy of 93%.

Table 10a. Manual occupant counts compared to thermal sensors counts from Room 110.

Start time	End time	Manual Count IN	Manual Count OUT	Sensor Count IN	Sensor Count OUT	Total Sensor Count # of Occupants	Total Manual Count # of Occupants	Difference
8:30	9:00	0	0	0	0	0	0	0
9:00	9:30	1	0	2	0	2	1	1
9:30	10:00	28	3	30	3	29	26	3
10:00	10:30	50	2	52	1	80	74	6

Table 10b. Manual occupant counts compared to thermal sensors counts from Room 117.

Start time	End time	Manual Count IN	Manual Count OUT	Sensor Count IN	Sensor Count OUT	Total Sensor Count # of Occupants	Total Manual Count # of Occupants	Difference
8:30	9:00	14	1	13	1	12	13	-1
9:00	9:30	16	1	20	1	31	28	3
9:30	10:00	25	5	24	5	50	48	2
10:00	10:30	70	28	70	30	90	90	0

6.3 Required Ventilation Calculations and Savings

In Table 12a, and 12b, the average number of occupants (measured and estimated) is calculated per hour timeslot over 1 week of data collection in Room 110 and Room 117. The average occupant values at each hour interval are used to generate minimum required ventilation rates using Equation 3. A comparison is made in Tables 11a and 11b to the original design ventilation which was based on the maximum number of occupants in the room and was designed to be continuously running.

Table 11a. Ventilation requirements based on average estimated, measured number of occupants and design occupancy in room 110 for the time of day noted.

Time of Day	Estimated Average # Occupants Nov 25-29	Estimated L/s *(Rp x Pz) + (Ra x Az)*	Measured Average # Occupants Nov 25-29	Measured L/s *(Rp x Pz) + (Ra x Az)*	Design Occupancy	Design Ventilation L/s (1960)
7:00	0.0	50.4	0.0	50.4	160	2265
8:00	0.0	50.4	6.9	76.6	160	2265
9:00	112.0	476.0	39.0	198.5	160	2265
10:00	102.3	439.0	33.3	176.8	160	2265
11:00	59.5	276.5	26.9	152.7	160	2265
12:00	125.4	526.9	47.5	230.9	160	2265
13:00	102.0	438.0	26.6	151.3	160	2265
14:00	119.4	504.1	20.3	127.7	160	2265
15:00	66.0	301.2	14.3	104.6	160	2265
16:00	86.0	377.2	25.4	146.8	160	2265
17:00	0.0	50.4	4.6	67.8	160	2265
18:00	97.0	419.0	31.6	170.3	160	2265
19:00	97.0	419.0	30.0	164.3	160	2265
20:00	69.0	312.6	0.0	50.4	160	2265
21:00	0.0	50.4	0.0	50.4	160	2265

Table 11b. Ventilation requirements based on average estimated, measured and design number of occupants in room 117 for the time of day noted.

Time of Day	Estimated Average # Occupants Nov 25-29	Estimated L/s *(Rp x Pz)* + *(Ra x Az)*	Measured Average # Occupants Nov 25-29	Measured L/s *(Rp x Pz)* + *(Ra x Az)*	Design Occupancy	Design Ventilation L/s (1960)
7:00	0.0	50.4	0.0	50.4	160	2265
8:00	0.0	50.4	10.5	90.2	160	2265
9:00	138.0	574.8	35.6	185.6	160	2265
10:00	84.8	372.6	30.4	165.9	160	2265
11:00	89.2	389.4	31.0	168.3	160	2265
12:00	80.8	357.3	37.2	191.9	160	2265
13:00	80.8	357.3	25.8	148.4	160	2265
14:00	72.5	325.9	23.1	138.3	160	2265
15:00	72.8	326.9	9.0	84.4	160	2265
16:00	86.5	379.1	5.5	71.4	160	2265
17:00	0.0	50.4	0.8	53.5	160	2265
18:00	42.3	211.0	3.9	65.0	160	2265
19:00	42.3	211.0	3.7	64.6	160	2265
20:00	46.0	225.2	0.0	50.4	160	2265
21:00	0.0	50.4	0.0	50.4	160	2265

Minimum required ventilation calculated based on average estimated number of occupants gives a range from 50.4 L/s at zero occupants to 574.8 L/s at the highest number of occupants in Rooms 110 and 117. Using the average measured number of occupants, the minimum ventilation requirements are calculated in a range from 50.4 to 230.9 L/s. The minimum required ventilation using the measured occupants is significantly less than that calculated for the estimated number of occupants. The original design ventilation is significantly higher than the minimum required ventilation generated by the estimated or measured number of occupants and today's standards.

Figure 8a and 8b represent the data presented in Table 11a and 11b to show the required minimum ventilation in calculated from hourly averages of measured and estimated number of occupants. The design ventilation original to the building is also shown

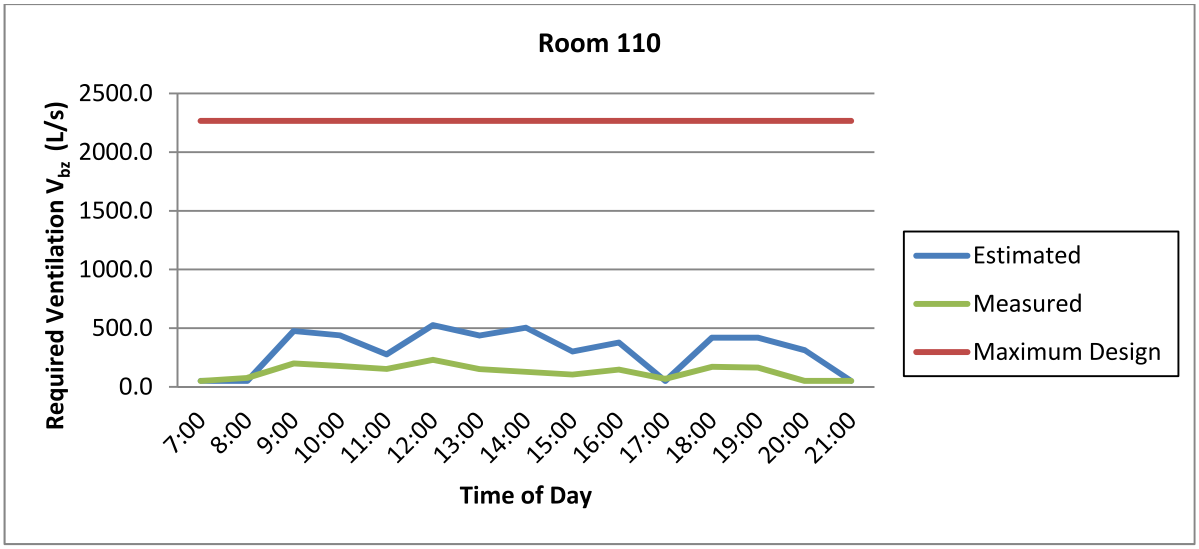


Figure 8a. Line graph showing required ventilation for average estimated and average measured number of occupants compared to the maximum design occupancy for Room 110.

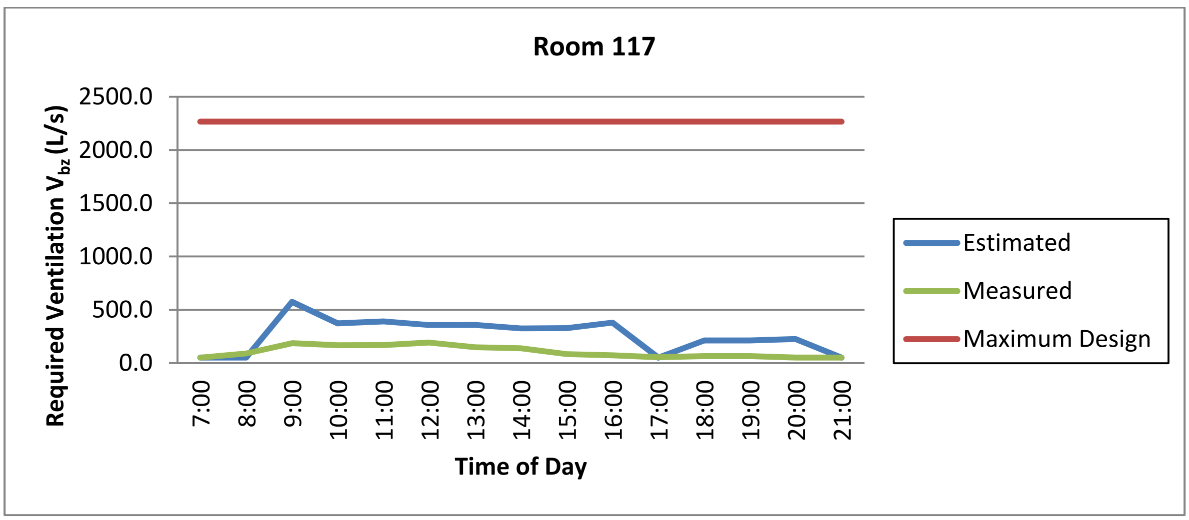


Figure 8b. Line graph showing required ventilation for average estimated and average measured number of occupants compared to the maximum design occupancy for Room 110.

An overall average of minimum required ventilation for both lecture rooms (combined) is calculated for the measured and estimated data. The measured number of occupants generates an average of 133 L/s from thermal sensor data, during occupied times. The estimated number of occupants generates an average of 373 L/s, during occupied times. The existing scenario in each case study lecture room has ventilation runs constantly at a relatively high level of 2265 L/s. Comparing 373 L/s to 2265 L/s of the original design is a significant difference; however, 373 L/s is based on an average and is likely to fluctuate throughout the day when calculated based on the number of occupants.

Figure 9a and 9b shows the hourly minimum required ventilation over the week of testing for each lecture room. The graphs show that using the Equation 3 to calculated the minimum required ventilation from the occupant data, the ventilation requirements fluctuate throughout the day. The graph shows no ventilation required during night time as the ventilation system could be turned off. Figure 8a and 8b shows the fluctuation of occupants throughout the day and the minimum required ventilation is at a maximum of approximately 600 L/s over the testing period reflecting the times when the most occupants are in the lecture rooms.

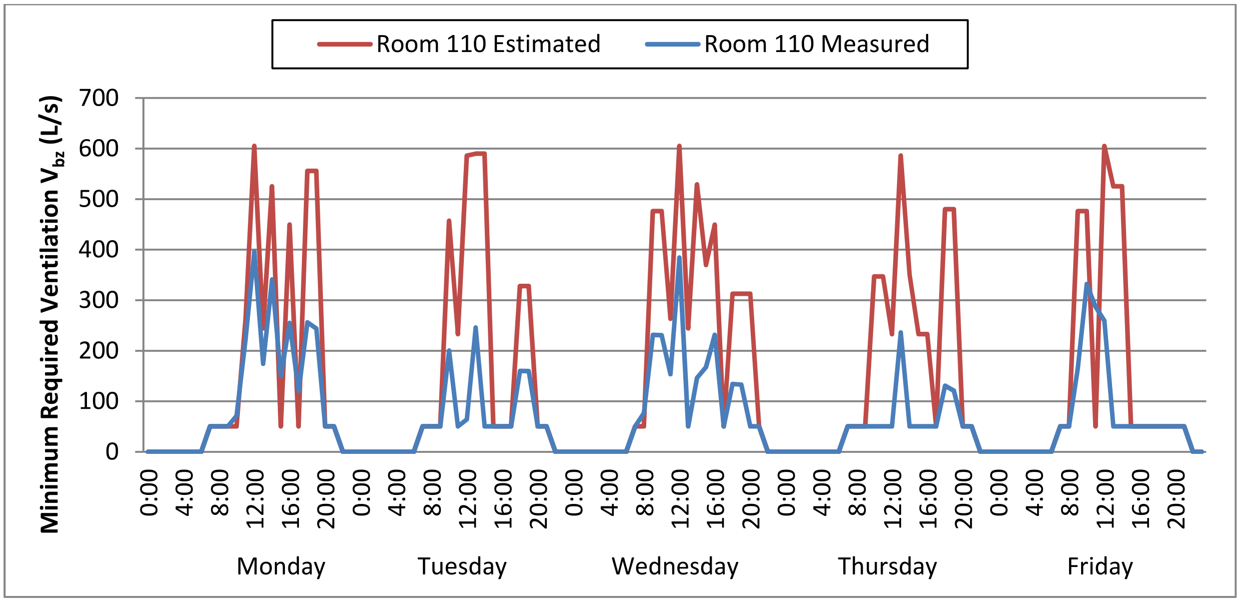


Figure 9a. Line graph showing minimum required ventilation based on estimated and measured number of occupants for Room 110 per hour and day.

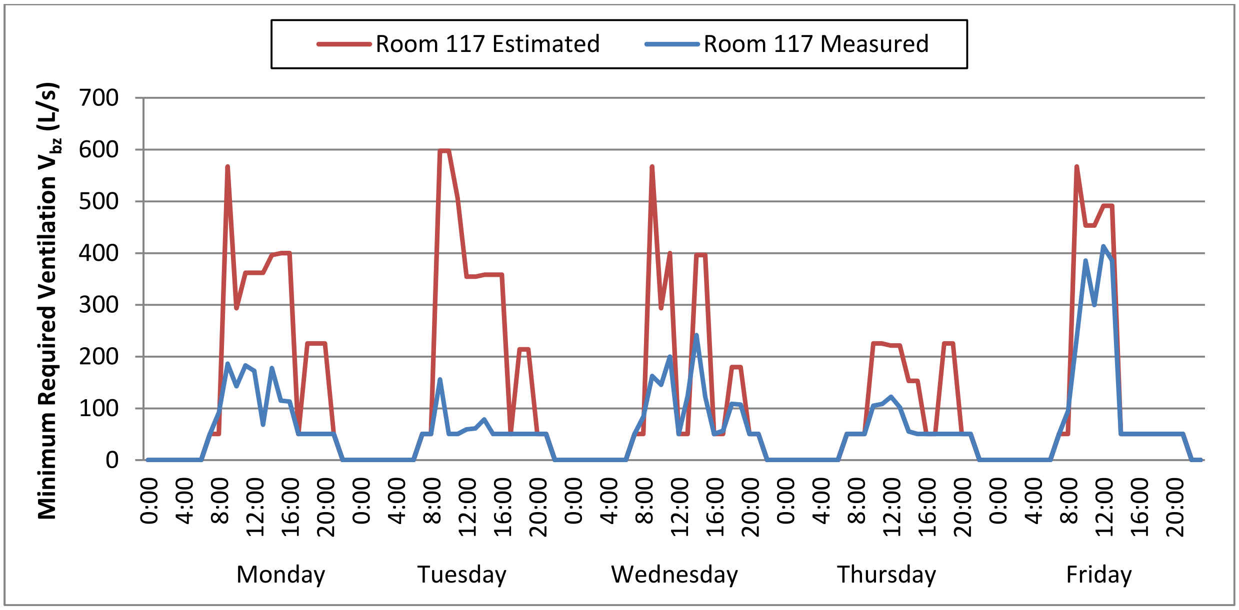


Figure 9b. Line graph showing minimum required ventilation based on estimated and measured number of occupants for Room 117 per hour and day.

Figure 10a and 10b shows the hourly minimum required ventilation from Figures 9a and 9b but compared to the original design ventilation. The area of the graph between the minimum required ventilation from estimated occupant data in Room 110 represents 93% reduction in ventilation from the original design compared to ventilation based on occupant numbers and today's standards. Room 117 has a similar percent reduction when compared to the original design ventilation, calculated at 94%. Using measured occupants the percent reduction in ventilation is calculated to be the same for each room at 97%.

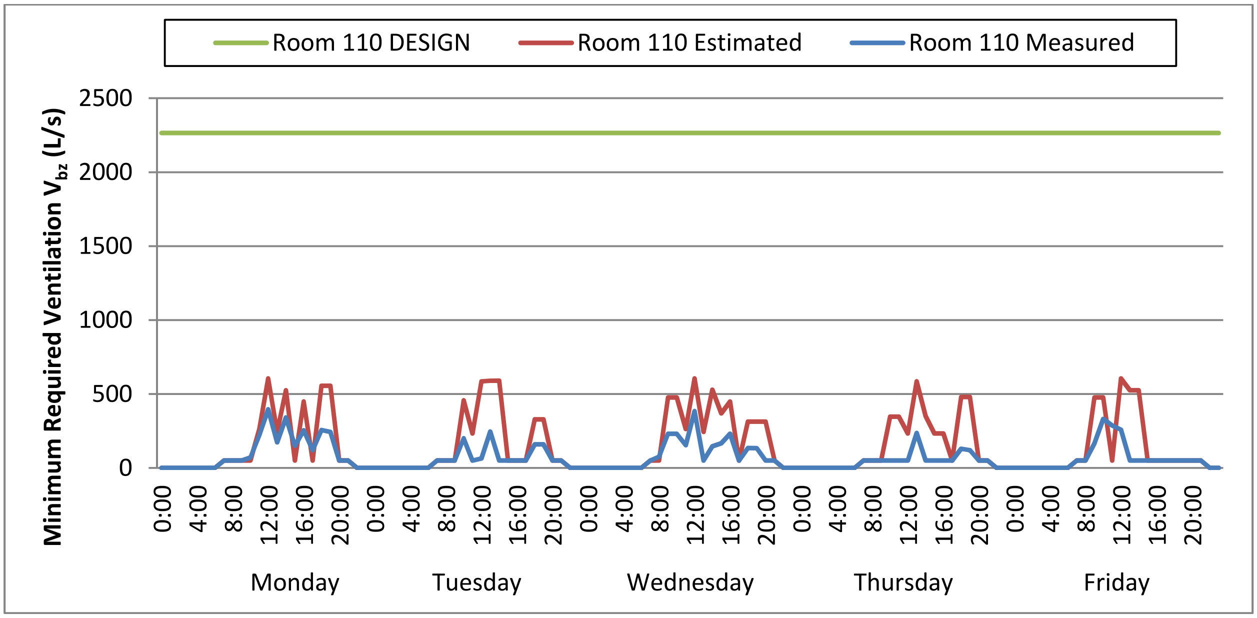


Figure 10a. Line graph showing minimum required ventilation based on estimated and measured number of occupants for Room 110 per hour and day, compared to original design ventilation.

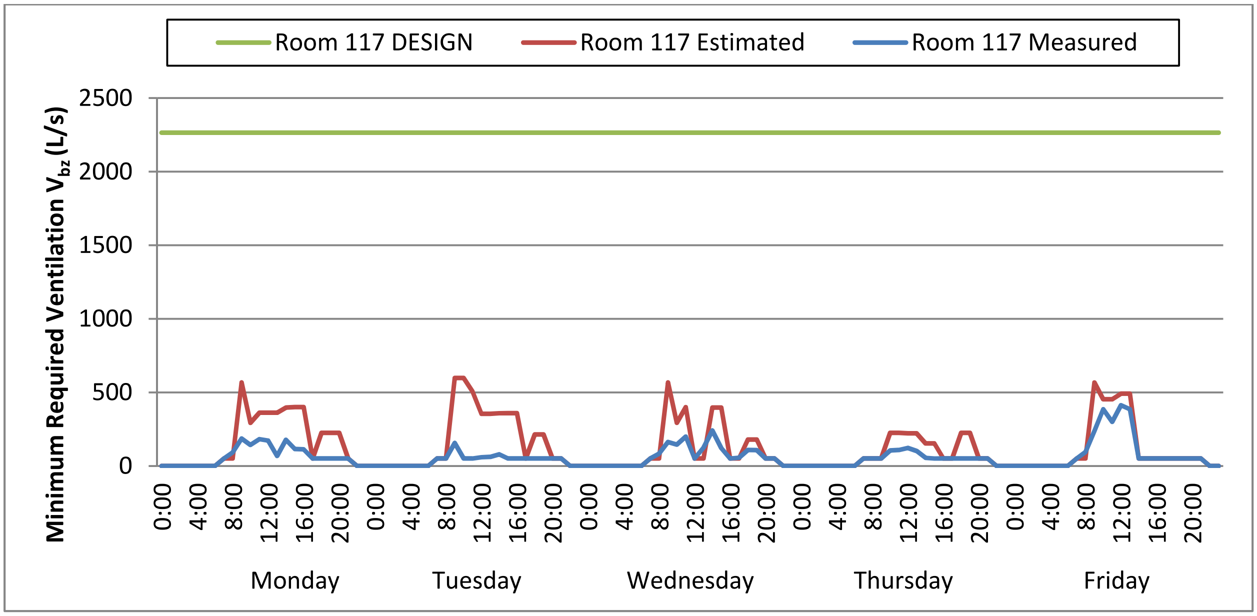


Figure 10b. Line graph showing minimum required ventilation based on estimated and measured number of occupants for Room 117 per hour and day, compared to original design ventilation.

6.4 Yearly Occupancy Schedule

The lecture rooms have un-occupied periods at night and on weekends, as well as holiday breaks and between terms. According to ASHRAE 62.1 current standards, during un-occupied periods, ventilation can be turned off. For the purpose of estimating the percentage of yearly occupied and un-occupied time, the occupied times are assumed to be from 7am to 9pm during the school week.

Table 12. Breakdown of occupied and un-occupied periods during the school year (University of Toronto).

Room Use	Number of days	Hours per day (hrs)	Hours per year (hrs)
Occupied Day times	201	15	3015
		Total Occupied hours	***3015***
Un-Occupied Night times	201	9	1809
Un-Occupied Weekends	104	24	2496
Un-Occupied No Classes (Holidays, Reading Week, Between Terms)	60	24	1440
		Total Unoccupied hours	***5745***

Table 13. Summary of yearly occupied and un-occupied periods, and average ventilation requirements based on measured occupancy.

	Hours per year	Per year percentage
Occupied Day times	3015	44.0%
Un-Occupied	5745	66.0%

Based on the University of Toronto academic schedule for 2013, the occupied period is calculated to be 44% of the year (160 of 365 days) and the un-occupied period is the remainder at 66%. This is summarized in Table 13.

6.5 Energy Savings Prediction

Table 14 lists the variables used for Equation 4 to calculate the energy use, fan consumption, of the existing ventilation system in the case study lecture rooms. The Horsepower (HP) for the existing fan providing ventilation for the lecture rooms in the case study was found to be 25 (Walker, 2013). Information for the motor efficiency at 85% and the load factor range from 70-80% were provided by Facilities and Services based on survey data of similar systems (Walker, 2013).

Table 14. List of variables and values used to calculate energy savings.

List of Variables	
Existing Fan Volume, CFM	4530
New (Reduced) Fan Volume, CFM	2720
Existing Total Fan Power, HP	25
New Total Fan Power, HP	7
Existing Motor Efficiency, %	85%
New Motor Efficiency, %	91%
Load Factor %	70-80%
Hours of operation (Existing)	8,760
Hours of operation (with DCV)	5,475

Comparing the minimum required ventilation based on the estimated number of occupants over the week tested to the original design ventilation, the reduction is over 90%.The ventilation cannot be reduced by 90% in the case study lecture rooms because there are many other variables to consider when reducing the ventilation in a space. Because the case study lecture rooms have a combined ventilation, heating and cooling system, the amount of heating and cooling would be affected if the ventilation is reduced to a very low level (Walker, 2013). In addition, the pressure and airflow in the space would be adversely affected if ventilation was reduced by 90% (Walker, 2013). If the ventilation system in the case study lecture rooms was separate from heating and cooling, the areas could further benefit from a DCV system design; allowing the ventilation to be driven by the number of occupants in the room and turned down close to the minimum required.

The energy use, fan consumption, for the existing system in the case study lecture rooms is estimated to be approximately 154,000 kWh per year using Equation 4. To determine a safe percent reduction of ventilation in the case study lecture rooms several variables were taken in to account. According to Walker (2013), based the on the design of the lecture rooms at the case study building, the occupancy information found in this study and pilot projects at other buildings at the University of Toronto, a 40% reduction was considered a safe reduction of ventilation in the lecture rooms. The following factors were taken into account; pressure in the space, static pressure, airflow and CO_2 levels (Walker, 2013). An estimated energy savings range can be calculated, if the ventilation is reduced by 40% using Equation 4.

The energy savings calculation also took into account the hours per year that the ventilation would be running. Occupied hours in a DCV design would be only 3015 hours compared to the existing design that is running all day, every day of the year. Using the variables listed in Table 14 and Equation 4, the energy use from a DCV system is calculated at a 40% reduction and 3015 hours a year. To calculate the energy use for a DCV system in the lecture rooms a range of fan load factors was used. The reduced ventilation calculated a range of 13,800 kWh to 12,000 kWh in fan consumption for one year. Using equation 5 to calculate the difference in energy use between existing and a DCV design, a range of 140,000 to 142,000 kWh energy savings is found. The overall energy savings is 92% and is a combined savings of 40% reduction of ventilation and 66% reduction of the ventilation system running or un-occupied hours when the system will be turned off.

7.0 Conclusions

7.1 Future Research and Developments

While some studies have looked at DCV with alternative occupancy methods, research has mainly focused on CO_2 sensor-based DCV suggesting a gap in the literature. This study has provided only a sample of the potential of DCV using thermal sensors as the measurement of occupancy. CO_2 sensor based DCV would likely result in similar occupant counts as those found with thermal sensor in the case study lecture rooms. CO_2 sensors would be a more complicated system to install temporarily for this type of study and could potentially have calibration errors.

Thermal sensors can be used as a tool to gain information on the actual number of occupants in a space and to investigate if DCV would be a good strategy in existing buildings. As shown in this study, occupancy data from thermal sensors can be used to calculate the potential energy savings in upgrading mechanical infrastructure of older buildings. An advantage to using thermal sensors in DCV is that the occupant information can be gained in real time. While in depth analysis on accuracy and reliability of the thermal sensors has not yet been explored in research, the technology is proving to work as expected in pilot studies at University of Toronto (Walker, 2013).

Given the recent research on the unreliability of CO_2 sensors and the complicated calibration process needed, thermal sensors could be a reasonable alternative. As shown in this study, the savings of DCV can be significant, especially in the retrofit of older buildings with high and low occupancy fluctuations. New technologies in occupancy sensors could help building owners realize a significant savings in energy through DCV. Demand control ventilation is a worthwhile strategy for energy savings and will likely grow in the building industry as technology develops.

7.2 Conclusions

This field study shows a sample of one week of occupant data collected by thermal sensors in a real lecture room setting. The thermal sensors counts were found to be consistent with the schedule and as expected, were consistently lower than the estimated number of occupants at 62%. The measured number of occupants over the week of testing, even at its maximum (96 people) is relatively low when compared to the number seats per room at 160. These values show that a DCV strategy would be beneficial in the case study building because the measured number of occupants is consistently lower than the maximum capacity the rooms can hold.

Calculating minimum ventilation requirement for case study lecture rooms, based on one week of occupant data, shows a significant reduction in the required ventilation as compared to the original design ventilation from the 1960s at approximately 90%. This comparison was done to show the potential savings if a DCV system was employed in the lecture wing of Ramsay Wright Laboratories Building and if the ventilation was a stand alone system without associated heating and cooling. Reducing ventilation by 40% and adjusting ventilation to the occupancy schedule could save as much as 142,000 kWh. The study shows that there is much improvement to be made in energy efficiency by using actual number of occupants rather than maximum occupancy to calculate ventilation.

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Appendix

Traf-Sys IP Thermal Sensor Specifications

Size	4.37" round x 2.75" deep
Casing	White ABS Plastic
Connection	RJ-45 female; daisy-chain connection among multiple sensors
Interfaces	Built-in Ethernet connection for configuration and data access; Serial Interface for configuraton using optional adapter
Mounting	Traf-Sys Mounting Base
Optimum Mounting Height	11.5 feet for 60 degree lens; 20 feet for 40 degree lens
Calibration	Built-in Web Browser configuration software requires the Microsoft Silverlight plugin (available as a free download from Microsoft).
Power	12-24 Volts DC; Optional Power Injector accessory available; Power over Ethernet (PoE) is not supported.
Environment	Indoor environments free from rapid changes in temperature or humidity.

Figure A1. Thermal sensor information (Traf-Sys, 2013).

	Monday 25-Nov	Enrolment	Tuesday 26-Nov	Enrolment	Wednesday 27-Nov	Enrolment	Thursday 28-Nov	Enrolment	Friday 29-Nov	Enrolment
7:00										
8:00										
9:00					EEB 362	112			EEB 362	112
10:00			MAT135	107	EEB 362	112	PHM 202	78	EEB 362	112
11:00	EEB322	56	EEB323	48	EEB 322	56	PHM 202	78		
12:00	MAT135	146	EEB202	141	MAT135	146	EEB323	48	MAT135	146
13:00	EEB321	51	SWK4107	142	EEB 321	51	EEB202	141	MAT133	125
14:00	MAT133	125	SWK4107	142	CHM138	126	CHM138	79	MAT133	125
15:00					CHM138	84	SOC395	48		
16:00	CSB328	105			CSB328	105	SOC395	48		
17:00										
18:00	FOR200	133	EEB266	73	PHL382	69	SOC212	113		
19:00	FOR200	133	EEB266	73	PHL382	69	SOC212	113		
20:00					PHL382	69				
21:00										

Table A2.1. Course Schedule and Enrolment for Room 110 from November 25 – November 29, 2013.

	Monday 25-Nov	Enrolment	Tuesday 26-Nov	Enrolment	Wednesday 27-Nov	Enrolment	Thursday 28-Nov	Enrolment	Friday 29-Nov	Enrolment
7:00										
8:00										
9:00	MAT137	136	SWK4102	144	MAT137	136			MAT137	136
10:00	JHE353	64	SWK4102	144	JHE353	64	ACT451	46	SOC218	106
11:00	PSY397	82	ACT145	120	ACT348	92	ACT451	46	SOC218	106
12:00	PSY397	82	EAS209	80			SOC362	45	SOC395	116
13:00	PSY397	82	EAS209	80			SOC362	45	SOC395	116
14:00	EHJ352	91	JLP374	81	EHJ352	91	MAT327	27		
15:00	ACT348	92	JLP374	81	EHJ352	91	MAT327	27		
16:00	ACT348	92	JLP374	81						
17:00										
18:00	ECO365	46	EEB263	43	ECO206	34	ECO206	46		
19:00	ECO365	46	EEB263	43	ECO206	34	ECO206	46		
20:00	ECO365	46								
21:00										

Table A2.2. Course Schedule and Enrolment for Room 117 from November 25 – November 29, 2013.

Photo 2. Room 117 at Ramsay Wright Laboratories Lecture wing.

	Room110					Room 117				
	Nov-25	Nov-26	Nov-27	Nov-28	Nov-29	Nov-25	Nov-26	Nov-27	Nov-28	Nov-29
0:30	0	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0	0
1:30	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
2:30	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
3:30	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
5:30	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
6:30	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
7:30	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
8:30	0	0	6.9	0	0	11.01	0	8.78	0	11.6
9:00	0	0	46.75	0	0	35.78	27.74	29.55	0	27.44
9:30	0	0	47.6	0	0	33.55	0	24.32	0	49.28
10:00	0	39.4	47.45	0	0	24.32	0	25.09	10.6	88.12
10:30	5.45	0	44.3	0	0	23.09	0	24.86	14.44	27.96
11:00	28.3	0	27.15	0	0	34.86	0	37.63	15.28	0
11:30	45.15	0	26	0	30.33	34.63	0	39.4	6.12	65.64
12:00	91	0	87.85	0	74.06	27.4	2.36	0	18.96	95.48
12:30	4.85	3.65	84.7	0	47.79	32.17	0.13	0	16.8	93.32
13:00	31.7	51.5	0	48.83	61.52	0	2.9	0.71	13.64	88.16
13:30	32.55	43.5	0	25.56	62.25	4.71	0	19.48	0	31
14:00	76.4	0	25.25	0	54.98	33.48	7.44	50.25	1.32	0
14:30	26.25	0	7.1	0	0	31.25	6.21	50.02	0.16	0
15:00	0	0	21.95	0	0	17.02	0	18.79	0	0
15:30	16.98	0	30.8	0	0	16.79	0	0	0	0
16:00	53.98	0	47.65	0	0	16.56	0	0	0	0
16:30	54.64	0	47.5	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0	0	0	0
17:30	18.35	0	0	0	0	0	0	1.64	0	0
18:00	54.2	28	22.05	21.13	0	0	0	15.41	0	0
18:30	48.05	28.85	19.9	20.86	0	0	0	15.18	0	0
19:00	50.9	28.7	21.75	18.59	0	0	0	14.95	0	0
19:30	32.75	26.55	18.6	0	0	0	0	8.72	0	0
20:00	0	0	0	0	0	0	0	0	0	0
20:30	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0
21:30	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0
22:30	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0
23:30	0	0	0	0	0	0	0	0	0	0

Table A4. People counting data from Thermal sensors at Ramsay Wright Laboratories Building Lecture wing.