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Mitigation Strategies for Overheating and High Carbon Dioxide Concentration within Institutional Buildings: A Case Study in Toronto, Canada

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Abstract: Indoor air quality and thermal conditions are important considerations when designing indoor spaces to ensure occupant health, satisfaction, and productivity. Carbon dioxide (CO_2) concentration and indoor air temperature are two measurable parameters to assess air quality and thermal conditions within a space. Occupants are progressively affected by the indoor environment as the time spent indoors prolongs. Specifically, there is an interest in carrying out investigations on the indoor environment through surveying existing Heating, Ventilation, Air Conditioning (HVAC) system operations in classrooms. Indoor air temperature and CO_2 concentration in multiple lecture halls in Toronto, Canada were monitored; observations consistently show high indoor air temperature (overheating) and high CO_2 concentration. One classroom is chosen as a representative case study for this paper. The results verify a strong correlation between the number of occupants and the increase in air temperature and CO_2 concentration. Building Energy Simulation (BES) is used to investigate the causes of discomfort in the classroom, and to identify methods for regulating the temperature and CO_2 concentration. This paper proposes retro-commissioning strategies that could be implemented in institutional buildings; specifically, the increase of outdoor airflow rate and the addition of occupancy-based pre-active HVAC system control. The proposed retrofit cases reduce the measured overheating in the classrooms by 2-3 °C (indoor temperature should be below 23 °C) and maintain CO_2 concentration under 900 ppm (the CO_2 threshold is 1000 ppm), showing promising improvements to a classroom's thermal condition and indoor air quality.

Keywords: Building Energy Simulations; energy efficiency; indoor environmental quality; indoor thermal condition; mechanical ventilation; Occupancy-based HVAC control

1. Introduction

In the design of the built environment, it is often a conventional practice to only consider the physical features of spaces whilst there are many other aspects largely influencing the indoor environmental quality (IEQ). For example, outdoor air ventilation rates are determined according to the conditioned area served by the Heating, Ventilation, Air Conditioning (HVAC) system and a default occupant density value defined according to building type [1]. This design method fails to take into account the effect of occupant density changing over time and their interaction with the immediate indoor environment. Therefore, researchers shift their focus to the adaptive design method, in which occupants are considered as integral parts of the whole comfort system of the building [2]. The number of occupants is modelled as a stochastic variable that can have an influence either by actively improving the thermal environment through occupant comfort control [2,3] or passively being the source causing discomfort in the space [4,5]. For example, an adult around 21–50 years old releases approximately 0.005 L/s [6] of carbon dioxide (CO_2) as a by-product of bodily function and heat of 150 W through convection, radiation, vapour, and sweat [7]. Table 1 lists the various IEQ measurement thresholds in non-residential buildings. Through measuring CO_2 concentration and indoor air temperature, this study aims to evaluate the contribution of high occupant density to undesirable indoor air quality and thermal conditions in a typical classroom.

Table 1. Indoor environmental quality (IEQ) measurements.

Contaminant	Health and Welfare Canada [8] Industrial Buildings and Non-Industrial Buildings		American Society of Heating, Refrigerating and Air Conditioning ASHRAE 62 [9] ASHRAE 55 [10]	Mitigative Measures
	Average Concentration (mg/m^3)	Maximum Allowable Concentration (mg/m^3)	Ventilation and Room Requirements	
Outdoor air requirement for ventilation (l/s/person)	-	-	10	ventilation rate control
Temperature (°C)	-	-	19.5–23 (Winter) 22.6–26 (Summer)	Control Heating, Ventilation, Air Conditioning (HVAC) heating and cooling system operation: Model Predictive Control [11]
Relative humidity (%)	-	-	30–60%	Control HVAC heating and cooling system operation: Model Predictive Control [11]
NO_2	9	-	-	Increasing ventilation airflow rate to between 2.5 to 5 air changes per hour (ACH) [12]
CO	55	440	-	
CO_2	9000	18,000	-	
O_3	0.2	0.6	-	
Lead	0.15	0.45	-	
Chlordane	0.5	2	-	

Multiple research studies concern the IEQ and thermal comfort of educational buildings. CO_2 is often used as one of the metrics for evaluating the IEQ since the presence of CO_2 at its threshold level is often an indication of an area of indoor pollutant concerns with poor ventilation [13]. Asif et al. [14] conducted an assessment of IEQ in four university buildings and investigated on the impact of different HVAC systems on building IEQ. They concluded that IEQ is heavily dependent on the type of ventilation system used. CO_2 levels were found to be highest in the university building utilizing non-centralized HVAC system. Krawczyk et al. [12] measured the CO_2 concentrations in two school buildings located in different climate and developed a model for estimating the concentration level. The study noted that the CO_2 concentration threshold is often exceeded within the first hour of occupancy. They suggested using air change rates of 2.5-5 to reduce the concentration. Zomorodian, Tahsildoost, and Hafezi [15] conducted a review on the thermal comfort in educational buildings and noted that most studies emphasize ventilation as a significant determining factor of IEQ and thermal comfort in classrooms. Ventilation demand increases with higher occupancy in classrooms [16]. University lecture halls are of particular interest for indoor air quality and thermal condition studies because students spend most of their time in lecture halls and energy savings are of importance to institutions [17]. This is also due to its occupancy pattern, usually with high occupant density that may dramatically vary throughout a day as students enter and leave the classroom in groups. If the HVAC system is not operated sufficiently, the heat and CO_2 accumulated during one lecture session may adversely affect the students in the following lecture session [18]. Architects and engineers use the thermal environment condition standards of ASHRAE 55, European Committee for Standardization CEN 15251: *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings*, and International Organization for Standardization ISO-7730: *Ergonomics of the Thermal Environment* as reference documents in their designs, but largely ignored (knowingly or unknowingly) the impact of transient occupancy pattern to the IEQ of classrooms. Studies [18–22] have expressed the inappropriate application of current standards, which are based on office buildings with a steady number of occupants, to the classroom environment due to different occupancy schedules.

Seppänen, Fisk, and Lei [23] conducted 24 case studies and concluded that a 2% decrease in productivity is observed for a 1 °C increase in air temperature above 25 °C. Charzidiakou et al. [24] suggest that IEQ assessments be mandatory as part of building regulations due to the interrelationship between thermal condition, indoor pollutant levels, ventilation rates, and CO_2 concentration. In their studies focusing on educational buildings, it is observed that keeping temperatures below 26 °C in summer and 22 °C in winter by outdoor air ventilation can limit the amount of Volatile Organic Compounds (VOC) below the threshold, above which sensory irritation is likely to occur. There is a correlation between high indoor air temperature and occupants' productivity as noted by Singh, Ooka, and Rijal [18]. Indoor air temperature and CO_2 concentration may be related because there is a higher likelihood of a space overheating above 25 °C when CO_2 concentration are above 1500 ppm [24]. Persily and de Jonge [5] identify that CO_2 accumulation in the space from occupants can cause indoor air quality concerns. CO_2 is reported to affect students' decision making and performance starting from 1000 ppm, and more significant effects when exposed to 2500 ppm [25]. CO_2 concentration of 1000 ppm is the threshold of safety defined by relevant standards and design guidelines [1,5], due to studies showing a correlation between cognitive function scores and CO_2 concentration [2]. Sick Building Syndrome (SBS), or the health effects caused by long term exposure to pollutants in the built environment, is prevalent in the presence of degraded indoor air quality [26]. The symptoms may include nasal congestion, dryness of eyes and skin, and headaches [27]. Norback et al. [28] conclude that indoor air temperature and CO_2 concentration are important considerations in indoor environment assessments. CO_2 concentration measurements are to be used to calculate accurate outdoor air ventilation rates.

The HVAC systems should be operated pre-actively in response to uncertain occupancy patterns anticipated in classrooms. Jaakkola et al. [27] relate SBS with inadequate mechanical ventilation rates as the primary cause. They identified that a reduction in ventilation rate caused a slight but significant increase in the occurrence of SBS symptoms. Due to the growing awareness of energy efficiency, research has been conducted over the past 25 years to investigate alternative HVAC controls for addressing the issues of internal heat gain without excessive energy consumption [11]. Kleiminger et al. [11] mentioned that occupancy prediction algorithms which control heating systems and temperature setpoint are effective in adjusting heating output throughout the day for the purpose of saving energy. The above-mentioned studies focus mainly on using ventilation as the strategy to remove excessive internal heat gain while lowering its corresponding energy consumption. CO_2 concentration, as another source of discomfort in indoor environments with high variable occupancy, is discussed in studies targeting CO_2 based ventilation control [29].

The above-mentioned literature shows that the IEQ in classrooms is an area of concern and prompted this study's investigation on the indoor condition during lecture hours. This study investigates how to regulate both the CO_2 concentration and indoor air temperature of classrooms via optimizing HVAC operation. The goal of this research is to evaluate the indoor environment of university lecture halls and propose mitigation strategies accordingly. Actual conditions are monitored, and a thermal sensation survey was done to identify and confirm the existing aspects of discomfort present in a classroom. The presence of discomfort as identified from on-site measurements and survey motivated further research. Specifically, strategies to optimally control the outdoor airflow rate and the heating output of the HVAC system will be proposed and evaluated using Building Energy

Simulation (BES) to determine if the cause of discomfort is related to the inadequacy of the existing HVAC system. The main objective is to propose an optimal HVAC operation scheme to improve the indoor environment in classrooms.

2. Methodology

The typical method of collecting data on occupants' activity level, clothing level, and thermal sensation rated on the ASHRAE standard 55 7-point scale is through the occupant questionnaire. This study uses on-site measurements and a questionnaire to grasp occupants' perception of the thermal environment. In addition, BES is commonly used for research in thermal comfort because of the abundant building information stored in the models and the ability to predict indoor thermal conditions. This study uses BES to assess options for reducing indoor environment discomfort as identified from on-site measurements. Section 2.1 will describe the on-site measurement procedures. Commonly used software includes EnergyPlus and eQUEST [2]. A study by Boudier et al. [30] couples a thermal comfort model with BES. The thermal comfort model uses the calculated mean radiant and air temperature at each time step to estimate perceived sensation votes, which then allows logic in the indoor condition controller to correct the set-point temperature at the next time step. BES can be used for investigating classroom thermal conditions and optimizing HVAC control systems while considering energy consumption, as shown in both Wang et al. and Saleem et al.'s studies [31,32]. In the studies, it was proven that BES results were able to match on-site measurements with minor observed discrepancies. Section 2.2 describes the simulation methodology and model inputs. Section 2.3 presents the proposed HVAC operation alternatives.

2.1. On-Site Measurement Procedures

Nine large classrooms in Toronto, Canada, ranging from 90 to 200 occupant capacity, are measured for indoor air temperature and CO_2 concentration. Results are consistent among the classrooms tested. One of the classrooms (which its occupancy capacity is the median among the nine classrooms tested) is selected as an example for discussion in this paper. A comparison of testing results is included in Table A1 of Appendix A. It is evident that the classroom selected for analysis has the highest maximum indoor air temperature, which is the main problem to be discussed in this paper. The classroom can hold a maximum occupancy of 160 people and is on the basement level of a 3300 sq. m building with a total of 5 stories. The testing spans from 9:00 am to 5:00 pm on a typical winter day with 4 classes taking place during those hours. Objective measures include a collection of data on indoor air temperature, relative humidity and CO_2 concentration using a portable data logger (temperature accuracy ±0.2 °C, relative humidity accuracy ±2.5% from 10% to 90%) and a high precision IAQ instrument (accuracy of ±50 ppm CO_2 ±2% of mv for a range of 0 to 5000 ppm CO_2). The measurements are taken at nine locations around the perimeter of the classroom with one located in the center (refer to Figure A1 in Appendix A). The dataloggers are placed underneath tables at a height of 1.0-1.1 m and at 1 m away from the perimeter walls. It is understood that ASHRAE Standard 55 requires measurements at 0.1 m, 0.6 m, and 1.1 m. However, the disruption to students must be minimized for this testing. In such a case, the dataloggers are placed underneath the desks. The readings are at a 1-min interval for temperature and a 10-min interval for CO_2. In addition, subjective measures are used to assess the occupant's thermal perception through a questionnaire relating to activity level, clothing level, thermal comfort on a 7-point scale, and students' satisfaction with the thermal condition (refer to Appendix B).

2.2. Simulation Methodology

A baseline model consisting of the classroom and its related building's characteristics is created. Energy simulations are conducted with two commonly used simulation software in the industry; eQUEST and EnergyPlus. EnergyPlus is used in companion with its Graphical User Interface (GUI), DesignBuilder, to facilitate the input of building descriptions into the calculations. The use of two simulation software is justified by the purpose of increasing confidence in the simulated model of the classroom. It provides an insight into the difference between the two respective software in considering internal heat gains and the options available to model custom HVAC operations. A study by Hong [33] considered the advanced capabilities of EnergyPlus compared to eQUEST and found out that eQUEST's limited feedback between HVAC and building loads calculations result in limited accuracy in zone temperatures. Therefore, this study aims to incorporate added value in comparing the two models against measured data for validation. Furthermore, this study focuses only on the heating season and the reported heating end-use energy is used to evaluate the efficiency of the HVAC system in providing the desired indoor temperature. Since zone level energy use is not directly obtainable from energy simulation results, the method used for determining zone energy consumption is as follows:

$$E_z(i) = \frac{Q_z(i)}{\sum_{i=1}^{n} Q_z(i)} \times E_b \quad (1)$$

where:

E_z (i) = Energy consumption of a zone (i) (kWh)
n = Total number of zones in the building
Q_z (i)= Heating load of a zone (i) (kW)
E_b = Energy consumption of the building (kWh)

Simulation Model Description-Baseline Case

Inputs and assumptions in the simulations are summarized in Table 2 for EnergyPlus and eQUEST models. Note that the building is simplified in the models (refer to Figures 1 and 2 for the building model visualization) as it is only concerned with the classroom in particular, treating the rest of the building as an adjacent zone. The weather data used for both simulations is the Canadian Weather for Energy Calculations (CWEC) 2016 Typical Meteorological Year (TMY) weather file for Toronto, ON International Airport [34]. Lecture schedules provided by the university are used as occupancy inputs. The classroom is conditioned by an Air Handling Unit (AHU). The system is a full air system and distributes conditioned air through air ducts with Variable Air Volume (VAV) terminals to each classroom. Considering the measured condition in the actual classroom and referencing Ontario Building Code (OBC) 6.2.1.2. for the design of indoor air temperatures [35], the heating setpoint temperature is defined as 21.2 °C.

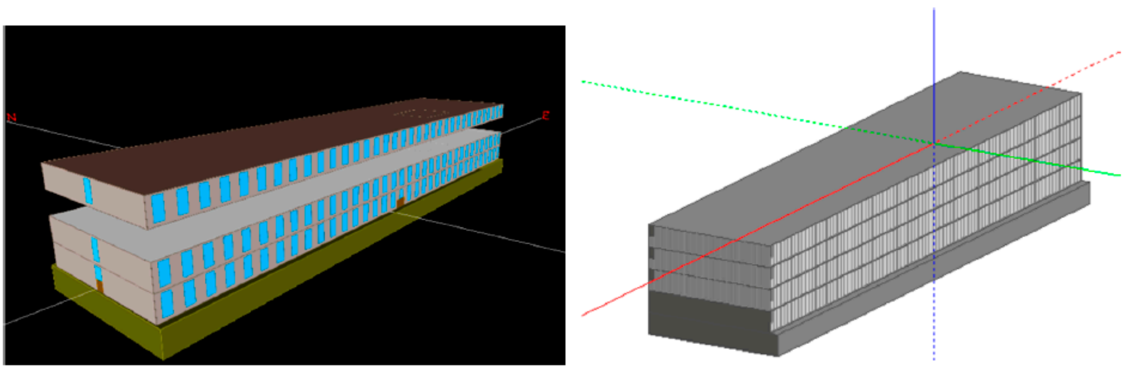

Figure 1. Geometric Visualization of the monitored building from eQUEST and DesignBuilder interfaces.

Table 2. Inputs to EnergyPlus and eQUEST Models.

Parameters	Input Values
Layout/Geometry	• Simplified rectangular geometry, whole building (5 floors) modelled • Classrooms treated as separate zone each, the rest of the building as one zone per floor • eQUEST: Floor Multiplier used (4 floors above grade)
Occupancy	• Lecture hours and number of students as ratios to the maximum occupancy (each week of the day; fall and winter term); summer 15–25% occupancy • Maximum occupancy: 160 people
Metabolic	• Seated and reading—metabolic factor 0.9
Heating/Cooling Setpoint Temperature	• Setpoint (occupied): 21.2 °C heating, 25.8 °C cooling • Setpoint (unoccupied): 18.3 °C heating, 28.8 °C cooling
Construction (EnergyPlus)	• External walls: 200 mm concrete block, 25 mm XPS, 10 mm gypsum plasterboard, Thermal Resistance in International System of Units (RSI): 2.16 m^2K/W • Below grade wall: 250 mm cast concrete, 12.5 mm gypsum plasterboard, 79.4 mm XPS (RSI: 2.80 m^2K/W) • Flat roof/ceiling: 250 mm concrete, 76.2 mm polyurethane, built-up roof, lay-in acoustic tile (RSI: 4.00 m^2K/W) • Internal partitions: plaster, 100 mm concrete block, plaster (RSI: 0.21 m^2K/W) • Ground floor: 200 mm concrete slab, 10 mm expanded polystyrene (EPS), gravel, 150 mm concrete slab (RSI: 2.88 m^2K/W) • Infiltration: 1.1 ACH
Construction (eQUEST)	• External walls: 152.4 mm concrete block, 76.2 mm polyurethane (RSI: 2.16 m^2K/W) • Below grade wall: earth contact, 304.8 mm cast concrete, 79.4 mm XPS (RSI: 2.80 m^2K/W) • Flat roof/ceiling: concrete, 76.2 mm polyurethane, built-up roof, lay-in acoustic tile (RSI: 4.00 m^2K/W) • Internal partitions: plaster, 100 mm concrete block, plaster (RSI: 0.21 m^2K/W) • Ground floor: 200 mm concrete slab, 10 mm expanded polystyrene (EPS), gravel, 150 mm concrete slab (R-value: 2.88 m^2K/W) • Infiltration: 1.1 ACH
HVAC System	• Fan Coil Unit (FCU) 4-pipe with water cooled chiller, water-side economizer (heating in January–May, September–December only, cooling in June–August only), default heater and chiller Coefficient of Performance (COP)

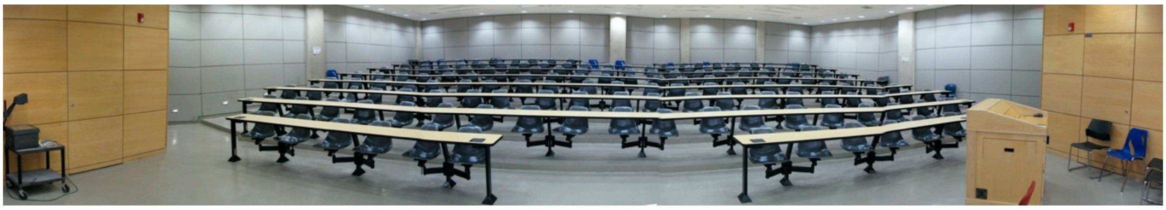

Figure 2. A view of the monitored classroom.

2.3. Proposed HVAC Operation Alternatives

Recent trends in improving existing buildings include retro-commissioning, where the focus is not on the equipment or additional technologies that can be used, but rather first considering the most efficient way to operate the HVAC systems [36]. Since the classroom considered in this study does not have windows, natural ventilation is not available. A study by Gao et al. [37] monitored the indoor climate of classrooms using a variety of ventilation methods including manually operable windows, automatically operable windows with or without exhaust fan, and balanced mechanical ventilation. The case with mechanical ventilation was favourable and performed better than naturally ventilated cases since it had a lower temperature still within thermal comfort range and a CO_2 level not exceeding 1000 ppm. A series of HVAC operation strategies considering higher outdoor airflow rate and pre-active controls using occupancy schedules described as follows have been implemented in the simulation as revised cases to regulate indoor air temperature and CO_2 concentration.

2.3.1. Optimum Outdoor Air Flow Rate

Equation (2) models the relationship between CO_2 concentration and the outdoor airflow rate. It is based on the balance of CO_2 from occupant respiration offset by air infiltration and mechanical ventilation, considering the assumption that the CO_2 concentration is fully mixed in the classroom when students are seated in a uniform pattern. Occupancy is modelled based on the schedule pertaining to the day of on-site testing. The model calculates the CO_2 concentration in the classroom based on infiltration Air Change per Hour (ACH), outdoor ACH, occupancy schedule, and the volume of the space. The calculated concentration is then compared to measured data to validate the model. The CO_2 concentration is regulated in revised case 1 with the optimized air change rate given by:

$$\frac{d(V \cdot c)}{d\tau} \cdot 10^6 = 10^6 \cdot N_{ppl} \cdot \mu - \left[\frac{V \cdot ACH_{vent+infil}}{3600} \cdot (c - c) \right] \tag{2}$$

where:

V = Total volume of conditioned room (m^3)

The volume of the classroom is 800 m^3

c = Concentration of carbon dioxide in indoor air (ppm)

106 = Conversion unit for concentration measured in ppm

N_{ppl} = Number of occupants

The number of occupants is a variable according to occupancy schedule

μ = Constant representing CO_2 concentration from respiration per person (m^3/min)

The estimated concentration is 0.36581×10^{-4} m^3/min

$ACH_{vent+infil}$ = Air change rate per hour from outdoor air ventilation and infiltration (#/hour)

The estimated ACH for infiltration is 1.1/hour referenced from United States Army Corps of Engineers (USACE) Standard for Air Leakage [38]

The ACH for outdoor air ventilation is a variable

C_o = Concentration of CO_2 in the outdoor air (ppm)

Average concentration in Toronto is 300ppm, referenced from ASHRAE Standard 62.1-2016 [9]
3600 = A constant, seconds in an hour

By increasing the value of the outdoor air change rate while keeping other variables as constant, the model estimated CO_2 concentration to be under 1000 ppm when using a 2.5 ACH. The rate is used in BES to correlate the decrease of CO_2 with a decrease in temperature. It is changed as a variable in the simulation to confirm the appropriate rate needed in the classroom to both lower temperature and CO_2 concentration. The use of 0.5 ACH in the model resulted in the CO_2 level similar to the measured data, thus validating the accuracy of the model. Therefore, it is estimated that mechanical ventilation is at 0.5 ACH in the existing classroom. This model indicates that the optimized air change rate is 2.5 ACH or above.

2.3.2. Occupancy-Based Pre-Active HVAC Control

Erickson et al. [31] noticed that most buildings are conditioned without predicting the actual number of occupants in the space to start corresponding adjustments to the HVAC system and have noted that occupancy prediction is useful for mitigating this issue. Several studies [11,39,40] investigated smart heating systems and HVAC control strategies that can adjust set-point temperature using occupancy prediction algorithms. In existing buildings, delayed action on the HVAC operation corresponding to the occupancy in the zone often leads to unnecessary over-conditioning and extra energy consumption. Dong et al. [41] and Rafsanjani et al. [42] consider the role occupancy plays in HVAC controls to minimize energy consumption. HVAC control based on occupancy patterns is often managed by Model Predictive Control (MPC) [11]. Dong et al. [41] claim that a 20% reduction in energy consumption can be achieved using proper MPC. The MPC used in Swaminathan et al.'s [40] study consists of an integrated control structure to track changing occupancy patterns. It also features a pre-cooling action that is implemented prior to occupancy increase. For example, outdoor airflow is drawn into the space half an hour before the room fills up with more people [40].

The proposed solution in this current study aims to reduce heating system output when the occupancy is expected to rise, similar to the concept of MPC as introduced before. Table 3 summarizes the modifications made in the revised cases to simulate proposed control on the heating and ventilation system based on occupancy. In revised case 1 done by CO_2 model (refer to Section 2.3.1), only the outdoor airflow rate was altered. Revised case 2 done by BES includes both increased outdoor airflow rate and occupancy-based heating availability schedule. Occupancy schedules (refer to Appendix C) and HVAC control were coupled in simulation by setting a heating availability schedule for the heating system to adjust the ratio of heating output into the zone based on expected occupant load. The objective of this study is to determine if the proposed adjustments made to HVAC operation can improve the IEQ of a classroom.

Table 3. Summary of Changed Variables Between Baseline Case and Revised Case.

Variables	Baseline Case	Revised Case 1-for Reducing CO_2	Revised Case 2-for Reducing Temperature
Outdoor Air Flow Rate ACH (#/hr)	0.5	2.5	2.5
Schedule	100% operated	N/A	To minimize heating availability when full occupancy is expected, the following schedule is implemented for the occupancy-based pre-active control:
			Occupancy: 100% Heating Availability *: 5% (close to off condition)
			Occupancy: 90% Heating Availability: 10%
			Occupancy: 80% Heating Availability: 15%
			Occupancy: 70% Heating Availability: 20%
			Occupancy: below 70% Heating: normal condition
			According to Figure 3, overheating occurs when occupancy is above 70% of maximum room capacity, therefore the pre-active control is activated only when occupancy is above 70%.

* Increments of 5% heating is added as occupancy is decreasing from 100% to 70%.

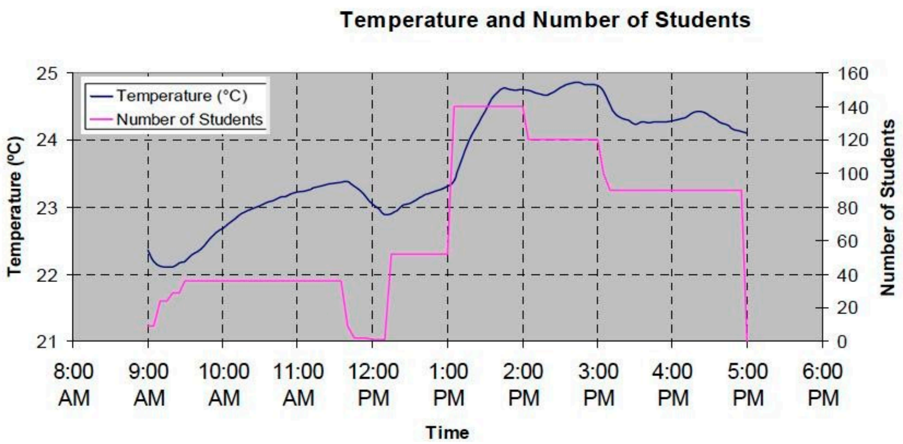

Figure 3. Measured temperature increase due to the addition of occupants in the classroom.

3. Results

First, the on-site measurements are presented to show the current thermal condition and indoor air quality of the classroom in Section 3.1. Section 3.2 presents the BES model validation for both EnergyPlus and eQUEST to confirm that the model is calibrated for further investigation. Sections 3.3 and 3.4 presents the results from the proposed HVAC operation schemes for reducing CO_2 and indoor temperature. By using these proposed strategies, the IEQ significantly improved in the aspects of preventing overheating. Lastly, Section 3.5 shows the Energy Use Intensity (EUI) resulted from using the proposed strategies.

3.1. Thermal Condition and Indoor Air Quality in the Classroom

Measurements confirm that the temperature increases throughout the day as more lectures take place. There is a strong correlation between the number of occupants and temperature increase, as well as CO_2 concentration (Figures 3 and 4). The indoor air temperature on a typical winter day reached up to 25 °C. The mechanical system was not activated because the measured temperature near the thermostat was higher than the upper limit of the setpoint dead band. The measured air velocity in the room did not exceed 0.2 m/s. In addition, the surveys showed that students expressed more satisfaction with the classroom's thermal condition when fewer occupants are present in the room. According to the thermal sensation survey, only marginally 80% of people ranked their thermal sensation to be within the acceptable thermal sensation range (−1 to +1) (refer to Appendix B). The occupant's comfort level is being compromised. The on-site measurements inferred a hypothesis that the reason for the high temperature and rising carbon dioxide concentration may be due to the lack of outdoor air ventilation in the space since heat and CO_2 accumulates in a high amount over the duration of the day. BES is therefore needed to investigate possible causes and solutions to the problems identified from on-site measurements.

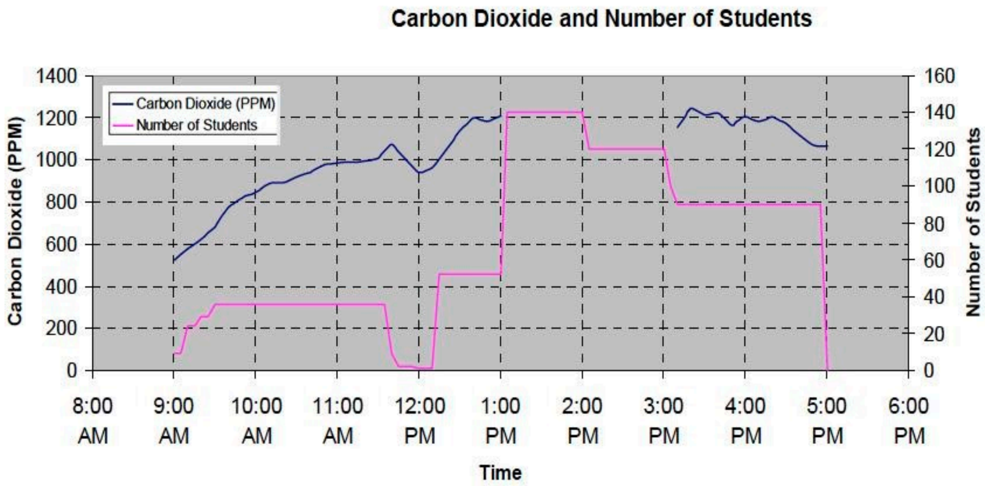

Figure 4. Increase in carbon dioxide due to the addition of occupants in the classroom.

3.2. Validation of Baseline Case

Similar to the measured data, the simulation predicted daily winter temperatures to be around the range of 18 to 25 °C, thus causing undesirable indoor thermal conditions due to overheating (refer to Figures 5 and 6). The shoulder seasons exhibit cases of overheating when the exterior temperature is increasing, due to the switchover between heating and cooling. The heating season is of interest in this study because Toronto has a semi-continental climate and is heating-dominated. Both eQUEST and EnergyPlus results show the fluctuation of temperature around the set-point in the classroom throughout the occupied hours and varying throughout the week depending on changes in occupant density. EnergyPlus results show that the temperature starts at 18 °C when unoccupied and rises to set point of 21 °C when occupied, then gradually increases to around 23 °C to 25 °C as the day goes on and the room fills with more occupants, before lastly returning back to 18 °C when unoccupied over the night. The peak air temperature noted is usually at the hours when the occupancy is the highest. Since indoor air temperature and CO_2 concentration continuously increase, this indicates that there may be insufficient outdoor air ventilation while the HVAC system is supplying heating output more than needed. As observed in Figure 7, both EnergyPlus and eQUEST models created in this study have predicted the trend of indoor air temperature fluctuations similar to the observed measured data.

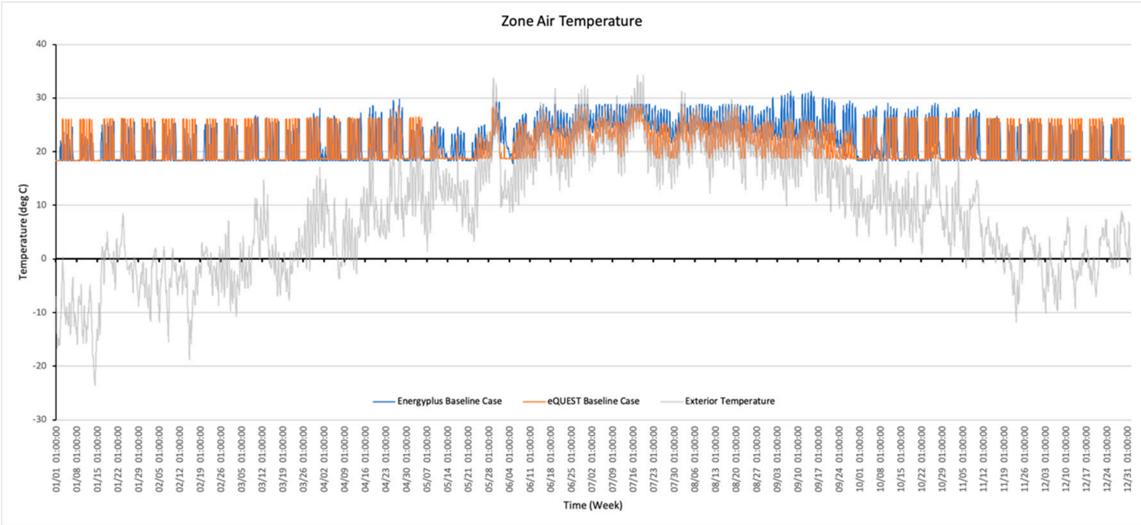

Figure 5. Simulated annual temperature profile from eQUEST and EnergyPlus showing overheating.

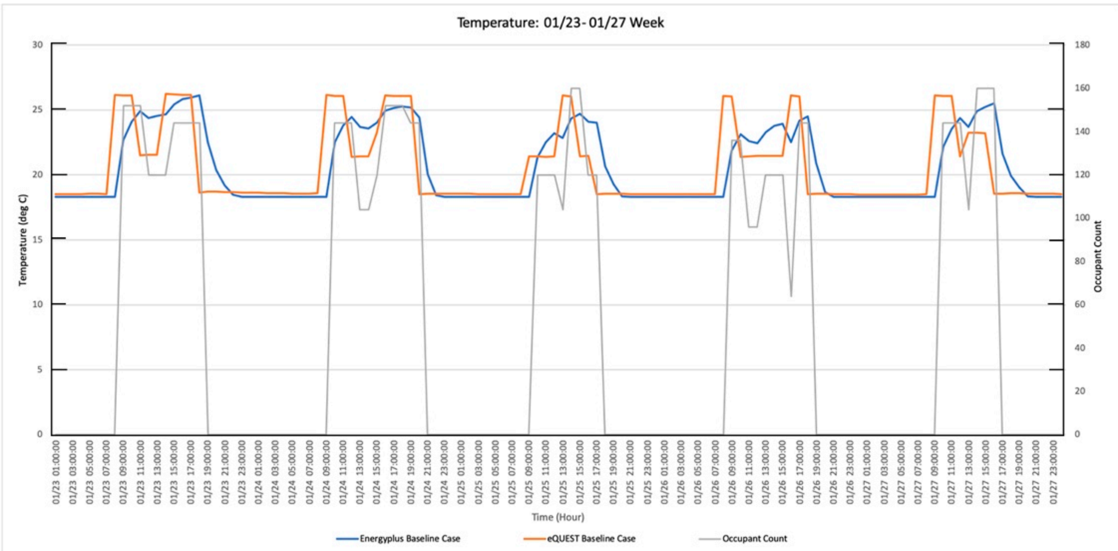

Figure 6. Temperature throughout a week, referencing occupants count.

Two statistical indices, Root Mean Squared Error (RMSE) and Coefficient of Variation of RMSE (CVRMSE) are used to evaluate the simulation models, as follows:

$$RMSE(i) = \sqrt{(\frac{1}{n})\cdot\sum_{j=1}^{n}[t_{a\_m}(j) - t_{a\_s}(i,j)]^2} \quad (3)$$

$$CVRMSE(i) = \frac{\sqrt{\frac{\sum_{j=1}^{n}[t_{a\_m}(j)-t_{a\_s}(i,j)]^2}{n}}}{M_{avg}} \times 100\%. \quad (4)$$

where:

i = 1: EnergyPlus result at timestep j, i=2: eQUEST result at timestep j (°C)
j = Timestep (seconds)
n = Total number of timesteps
t_{a_m} (j) = Measured indoor air temperature (°C)

t_{a_s} (i, j) = Simulated indoor air temperature for instance i (°C)
M_{avg} = Average of the measured indoor air temperature, $M_{avg} = \left(\frac{1}{n}\right) \cdot \sum_{j=1}^{n} t_{a\_m}(j)$ (°C)

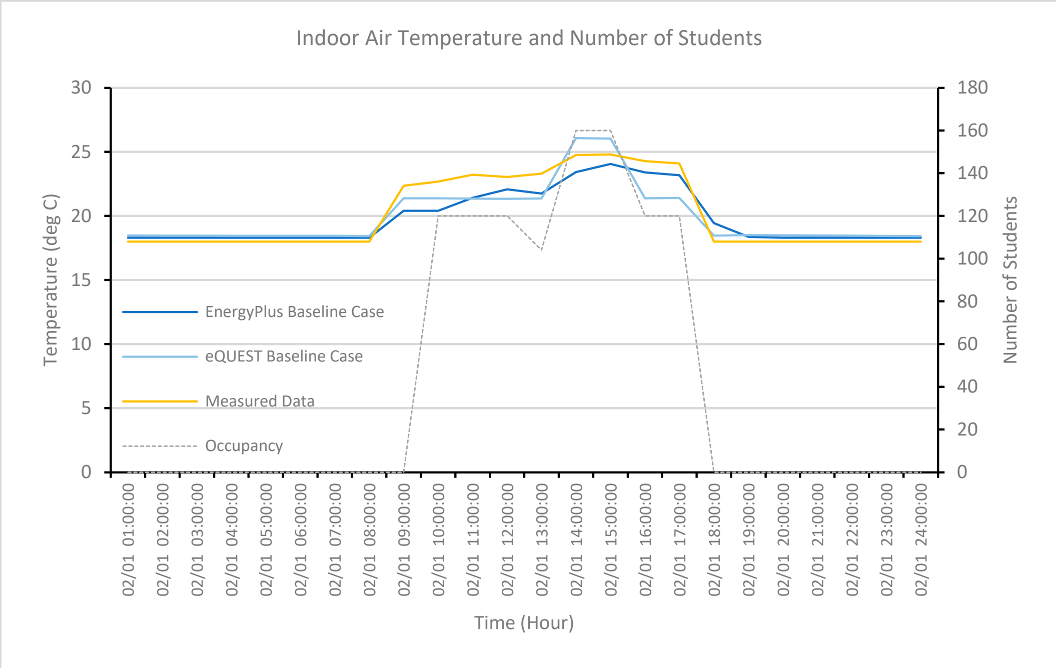

Figure 7. Simulated indoor air temperature compared to the measured data during occupied hours, referencing occupants count.

The CVRMSE of the simulated and measured data in this study is closer to the lower value of the standards' range (refer to Table 4). Standards such as ASHRAE Guideline 14, International Performance Measurement and Verification Protocol (IPMVP), and Federal Energy Management Program (FEMP) indicate the acceptable accuracy range to be between 5-20%, with 0% being the perfect case [43]. RMSE and CVRMSE are negatively oriented scores. The simulated results tend to underestimate the temperature most of the time. This implies that the simulations are under-predicting the impact of occupancy density and other internal gain factors on the increase in indoor air temperature. However, at times of highest occupancy during the day, eQUEST results predicted a higher temperature than the actual measured data (refer to Figure 7).

Table 4. Error Indices Calculated to Evaluate the Predicted Model against Measured Values.

Model Data	Root Mean Squared Error RMSE (°C)	Coefficient of Variation of Root Mean Squared Error CV-RMSE (%)
1-EnergyPlus Results	1.47	6.23
2-eQUEST Results	1.88	7.95

Robert et al.'s paper [44] which also evaluates simulation models, is used as a reference for benchmarking the error values. RSME is used as a validation index because it is more sensitive to deviations than other indices such as Mean Absolute Error (MAE), and is used when larger errors are undesirable. CVRMSE is considered in Hong et al.'s paper [43] as a metric for reliability analysis between hourly baseline models and existing buildings. CVRMSE is an indication of how well the simulation matches the variation in measured values [45]. CVRMSE is used in addition to RMSE for normalizing by the mean value of measured data to avoid ambiguity. The work by Rallapalli [46] has noted a difference between eQUEST, EnergyPlus, and actual measured data. However, Rallapalli did not discuss in detail the comparison between measured and simulated results. Moreover, there are more literature on comparing simulated energy consumption to empirical data than for indoor air temperature. Studies that compare measured indoor temperature with simulations notice that there is a temperature difference of 1 °C and is mostly during the daytime where occupancy and solar radiation are the affecting factors [17,47].

3.3. Revised Case 1-Reduction in CO_2 Concentration

In Figure 8, the baseline model (in blue) which used 0.5 ACH has a comparable pattern with the measured data (in yellow). As a revised case, the airflow rate is increased to 2.5 ACH (refer to Section 2.3.1), which resulted in CO_2 concentration below 1000 ppm, which is the acceptable level according to ASHRAE Standard 62.1-2016 [9] (refer to Figure 8). The growth in concentration due to increased occupancy is at a slower rate than the baseline case. Based on this result showing 2.5 ACH as the optimal air change rate which can lower CO_2 concentration, it is recommended that the classroom should be operated with such an increased air flow rate.

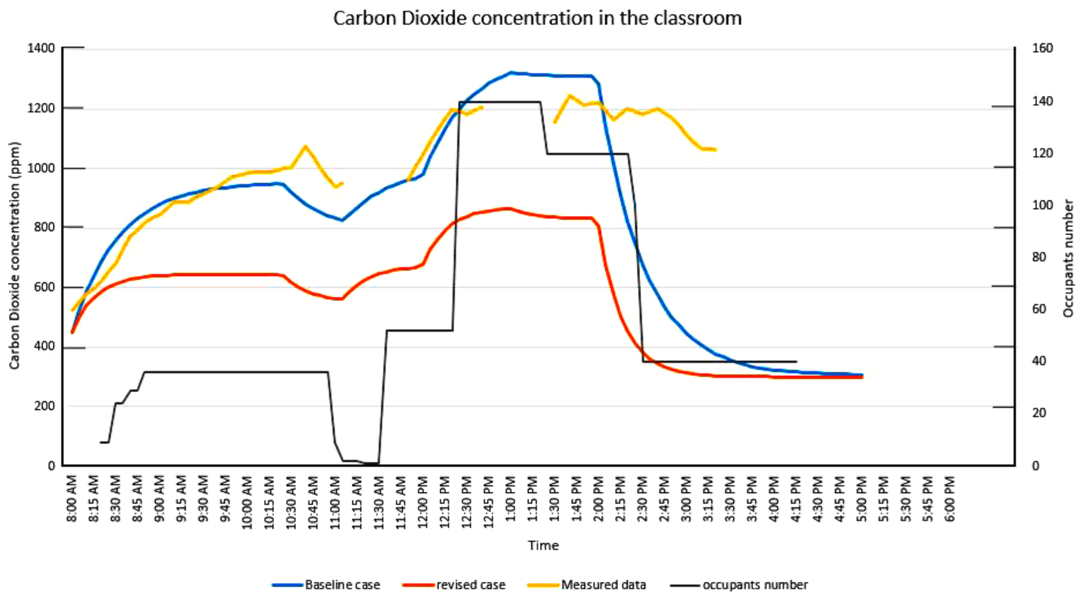

Figure 8. Carbon dioxide concentration compared between measured and simulated model. Note that the measured data is segments due to the disruption of the equipment; however, the concentration increase can still be observed.

3.4. Revised Case 2-Reduction in Hourly Indoor Air Temperature to Minimize Overheating

Thermal modelling confirms that the airflow rate used in revised case 1 is effective in reducing the indoor air temperature. The indoor air temperature overheated to around 24–26 °C in the baseline cases, while the revised case controlled the temperature under 23 °C. Figures 9 and 10 show the temperature in January. At times when the exterior temperature is relatively high, the indoor air temperature for the revised case is 23 °C, which is close to the set-point temperature of 21 °C and, thus, would not be considered overheating (refer to Figures 11 and 12). This is due to increasing the ventilation airflow rate to 2.5 ACH and using an occupancy schedule for controlling heating.

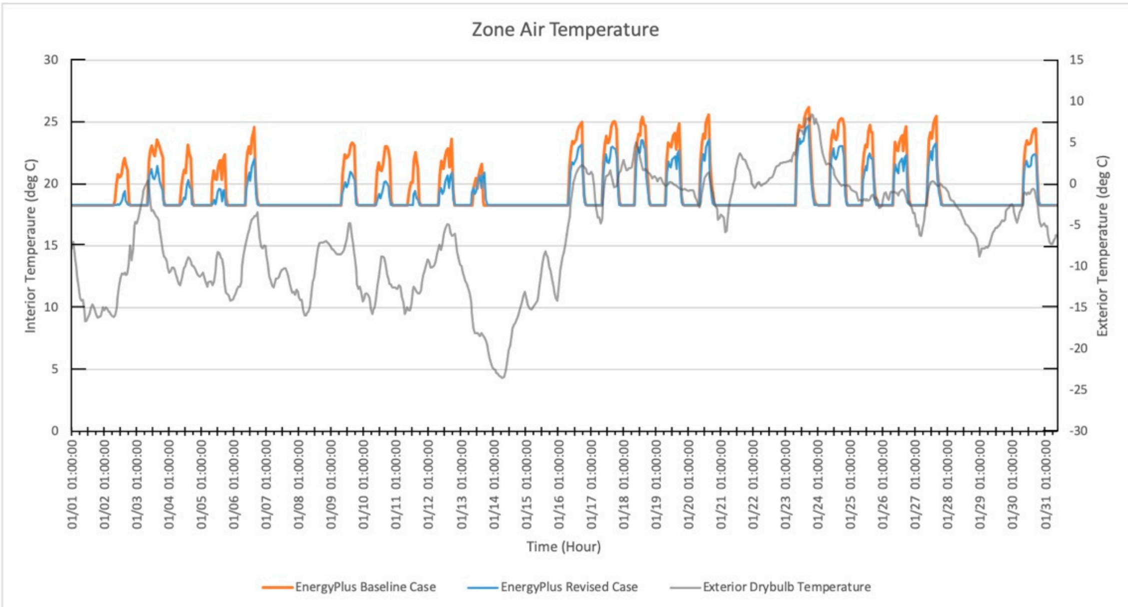

Figure 9. EnergyPlus temperature results in January with baseline case (red) and revised case 2 (blue) showing a reduction in temperature when outdoor airflow rate is increased.

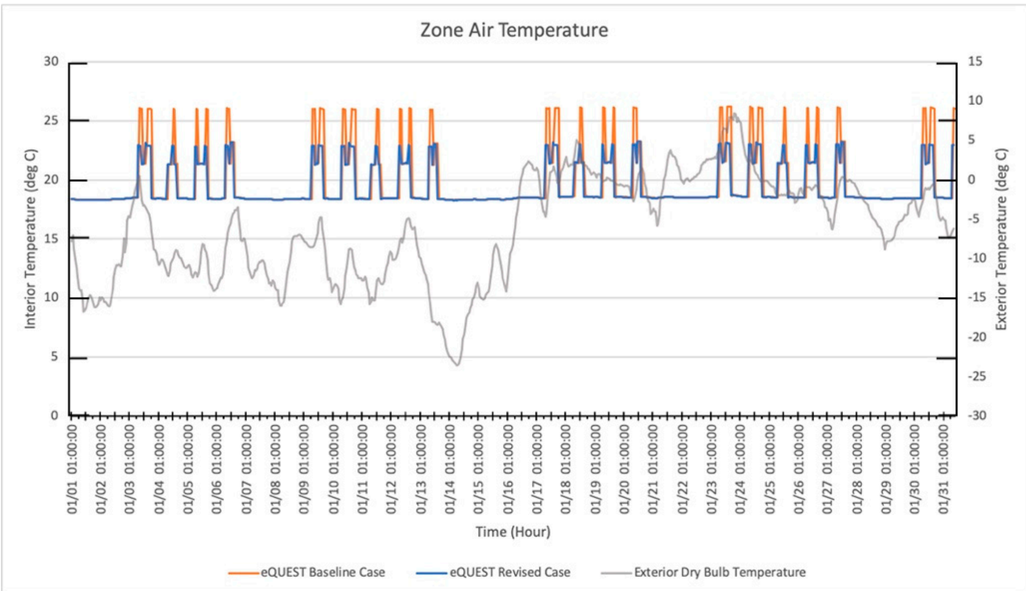

Figure 10. eQUEST temperature results in January with baseline case (red) and revised case 2 (blue), showing a reduction in indoor air temperature when outdoor air flow rate is increased.

3.5. Energy Consumption

Since the objective is to mitigate wintertime overheating, only heating energy consumption will be reported in the following. Heating energy forms a large part of a building's total energy consumption. Natural Resources Canada reported that within the energy end-use breakdown of commercial and institutional buildings, 48% are accounted for from space heating, while only 5% are from space cooling [48]. The Energy Use Intensity (EUI), reported in Tables 5 and 6, shows the impact that the mitigation strategies have on the energy consumption of each model. The reduction of heating energy input into space reduces energy consumption, but this reduction is not sufficient to offset the added energy from operating mechanical ventilation. However, the consumption from mechanical ventilation does not result in a large increase in total consumption. Note that the eQUEST results are consistently higher than the EnergyPlus results, which is in agreement with Rallapalli's study [46]. The difference is more noticeable in the zonal energy use due to the variation in the ratio between zone and the sum of all zones' heating load (refer to Section 2.2). Since indoor air temperature simulated by each model is not exactly the same, there will also be evident contrast in the reported energy consumption. Measured data is also unavailable for each zone because the university does not use submetering for their facilities. The main finding from simulating energy consumption is to confirm that the increase in airflow rate would not result in a large addition of energy use.

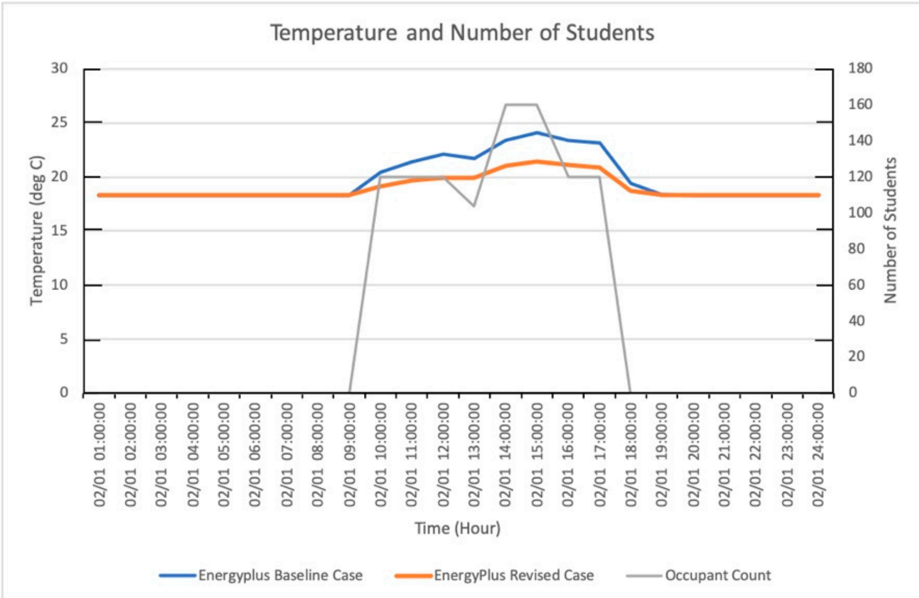

Figure 11. EnergyPlus temperature results of a day, showing a reduction in indoor air temperature.

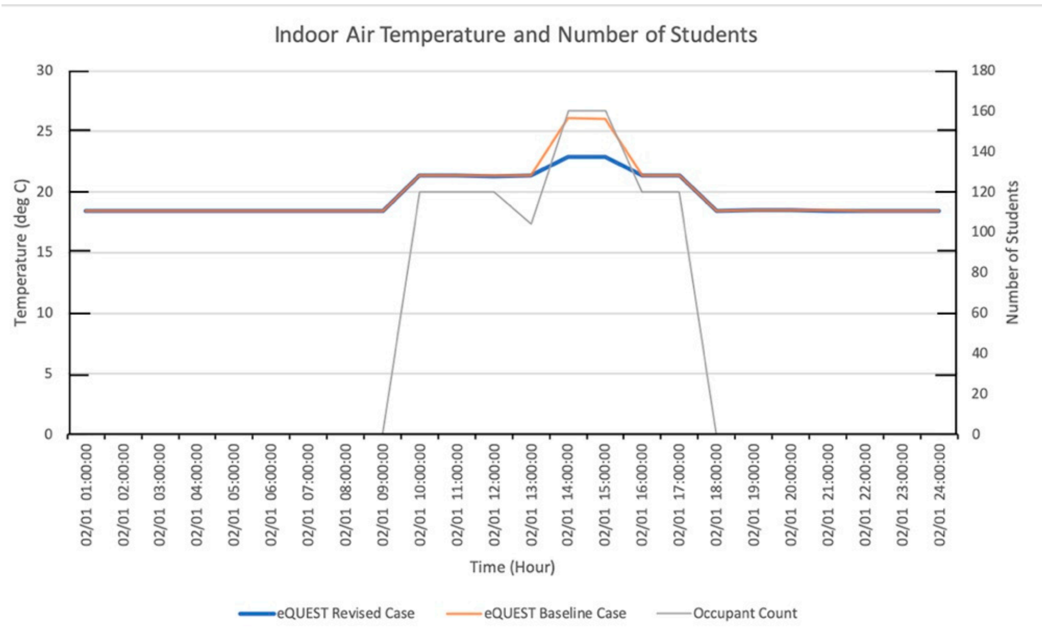

Figure 12. eQUEST temperature results of a day, showing a reduction in indoor air temperature.

Table 5. Building Level Energy Use Intensity of Revised Cases from EnergyPlus and eQUEST (all figures in kWh/m^2·year).

	Baseline Case Building EUI	Revised Case 2 Building EUI-without Energy from Mech Vent.	Revised Case 2 Building EUI-with Energy from Mech Vent.
EnergyPlus	103.94	103.74	124.72
eQUEST	120.27	120.16	141.25

Note: Building Total Floor Area is 21,000 m$^{2.}$

Table 6. Zonal Energy Use Intensity of Revised Cases from EnergyPlus and eQUEST (all figures in kWh/m^2·year).

	Baseline Case Building EUI	Revised Case 2 Building EUI-without Energy from Mech Vent.	Revised Case 2 Building EUI-with Energy from Mech Vent.
EnergyPlus	87.66	82.69	109.56
eQUEST	128.79	126.63	149.16

Note: Classroom Zone Area is 200 m^2.

The energy consumption including ventilation and heating in a day with occupied lecture hours in mid-day and non-occupied at other hours shows the efficacy of the proposed strategies. Figure 13 shows that the energy consumption from the baseline case (red datapoints) is increased during expected beginning of school hours (8:00). The energy consumption is high even when there are no occupants, and does not decrease in anticipation of upcoming high occupancy load. The decrease of energy demand responses to the increase in temperature starting at 13:00 when a lecture takes place. On the other hand, the Revised Case 2 with proposed strategies (blue datapoints) that take into consideration occupancy predictions steadily cumulates throughout the day except for the hours with increased occupancy where a higher energy consumption is due to increased mechanical ventilation. The cumulative energy consumption for baseline is 174 kWh while it is 186 kWh for the revised case. The increase in energy consumption is not drastically higher nor at a disadvantage, given that the IEQ and thermal condition are improved.

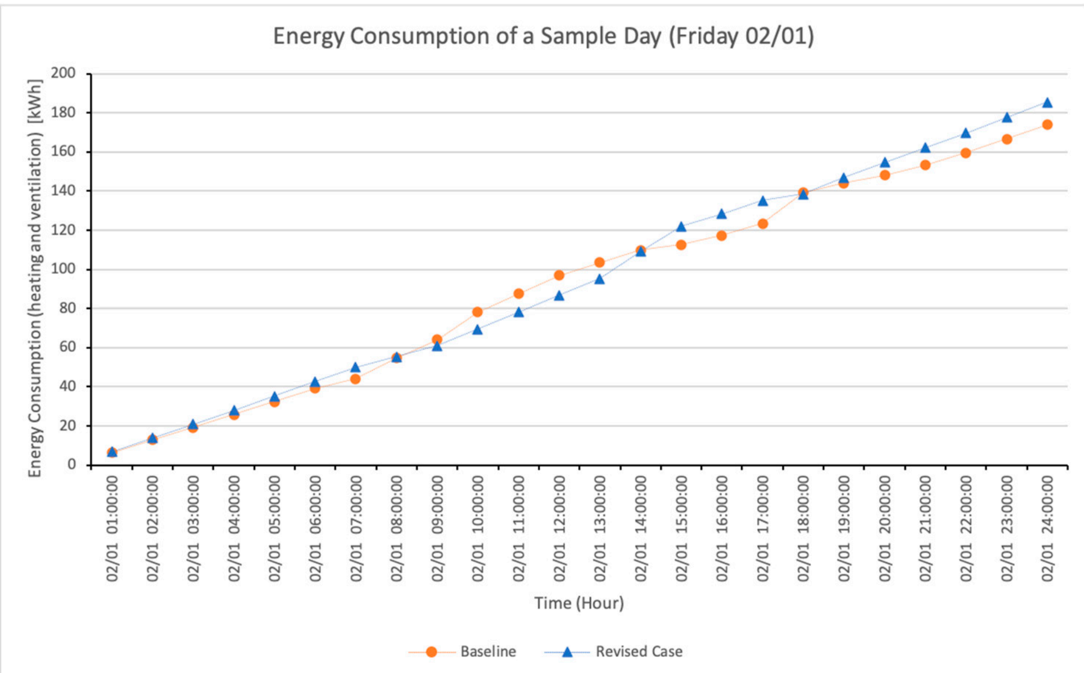

Figure 13. Cumulative Energy Consumption (Mechanical Ventilation and Heating inclusive) of a day, comparison between baseline and revised case.

4. Discussion

The on-site measurements confirmed that the classroom is overheated in the wintertime and CO_2 concentration is accumulating with the increase in occupancy density. In addition, the questionnaire confirms that students are not satisfied with the classroom comfort level. It is evident that occupancy is a major heat and CO_2 source while the space does not have adequate methods of dissipating such heat and contaminants.

Simulation identified efficient HVAC operation to be dependent on outdoor airflow rate and quantity of heating output determined by schedules. It provided an insight into the importance of occupancy in BES and HVAC operation. Tables 7 and 8 summarizes the main results of the revised cases, showing reduced CO_2 concentration and the indoor air temperature remained closer to the intended indoor air temperature set-point during the heating season. The previously measured CO_2 concentration is exceeding the ASHRAE standard of 1000 ppm as the acceptable range for indoor air. Therefore, university lecture classrooms should include systems for increased outdoor air ventilation such as the use of a heat recovery ventilator (HRV) or an energy-recovery ventilator (ERV).

Table 7. Reduction in Carbon Dioxide Concentration.

Control Strategy	Infiltration Rate ACH (#/hour)	Mechanical Ventilation ACH (#/hour)	Zone Air Maximum CO_2 Concentration (ppm)	Zone Air Average CO_2 Concentration (ppm)	Fan Energy Consumption (kWh/hour)
Baseline	1.1	0.5	1320.45	818.18	0.009
Revised	1.1	2.5	864.06	573.68	0.047

Table 8. Elimination of Overheating.

Control Strategy	Mechanical Ventilation ACH (#/hour)	Zone Air Maximum Temperature (°C)	Zone Air Average Temperature-Considering Occupied and Unoccupied Hours (°C)
Baseline (EP)	0.5	24.06	19.73
Baseline (EQ)		26.07	19.82
Revised (EP)	2.5	21.46	19.02
Revised (EQ)		22.93	19.55

This research shows that occupant satisfaction is jeopardized when the HVAC system is not adjusting its operation until the occupant behaviour causes a disturbance on indoor air temperature, which is in agreement with Leaman and Bordass's findings [3]. Similarly, it is evident through the results of this current research that the constant change in occupancy density throughout the day causes high air temperature and unsatisfactory indoor air quality within the space. Increasing outdoor air ventilation and scheduling the heating availability dynamically according to occupancy density is therefore proven in this study as effective solutions to stabilize the indoor air temperature and CO_2 concentration. It aligns with the values of research related to Model Predictive Control [41] and supports the development in set-point temperature algorithms tuned with the estimation of upcoming occupancy load.

5. Conclusions and Future Works

The assessment conducted in this study raises the concern of high indoor air temperature and CO_2 concentration within university lecture classrooms. The assumption of static occupancy, as adopted in thermal comfort standards such as ASHRAE 55, is not sufficient for classrooms. It is evident that existing HVAC operation strategies must be improved, and the interventions proposed above have been effective in properly controlling indoor air temperature and CO_2 concentration. The key changes to HVAC operation are identified as increasing outdoor air ventilation and controlling the system according to dynamic occupancy density. If institutional buildings adopt these interventions, the benefit would be improved thermal condition and indoor air quality. It will be a stride towards improving students' productivity and satisfaction towards their learning environment.

Ongoing research includes updating measurements of air temperature in various classrooms over a longer period of time and considering more thermal comfort parameters. Measured data from a winter school term will help calibrate the model (baseline case) more accurately, as well as provide more occupancy data over a longer period of time throughout the year. Furthermore, only the wintertime overheating effect has been analyzed in this study, while summertime subcooling may also be an issue present in the classrooms. In addition to hourly indoor air temperature and CO_2 concentration comparison between measured and simulated data, other parameters to assess thermal comfort such as relative humidity and mean radiant temperature may also be compared using BES, similar to what has been done in Ahmad et al. and Chenari et al.'s research [49,50]. Chenari et al. [50] simulated occupancy and CO_2 based demand-controlled mechanical ventilation strategies using EnergyPlus to explore and arrive at a conclusion regarding the impact that schedule and ventilation strategies have on energy consumption and indoor air quality. In this way, there can be more insight into optimal ventilation strategies that controls a wider range of indoor air quality and thermal condition parameters.

Moreover, note that the current HVAC operation changes implemented in EnergyPlus and eQUEST are theoretical and are to be tested in actual practice to determine its validity in influencing the indoor environment. Changing the heating schedules based on occupancy is a variable that is changed within energy simulation, but the actual implementation of these strategies to the classroom is not within this research's current scope. By observing the positive effects that resulted from these variations, it indicates a possibility of improving HVAC operational strategies in similar ways, but with practical and tangible methods such as through the use of sensors. This study has demonstrated that BES can identify overheating and high CO_2 concentration to develop possible solutions. However, an overarching practical issue that most energy modelers face is the time and effort required to collect adequate data and develop reliable energy models. Detailed energy modelling using building simulation programs requires many inputs, and modelers may not have full knowledge of each input's relative importance to simulation outcomes, level of uncertainty, and the appropriate default values to use. This issue is exacerbated when actual or realistic data (i.e., occupancy, operational schedules, infiltration) are not available while the use of typical input values or assumptions is not appropriate for the application [51]. In the future, BES will provide unprecedented value in assisting the design and operation of low energy buildings that address occupancy comfort. It is hopeful that more HVAC operation schemes can be tested for effectiveness in improving the thermal condition and indoor air quality through building simulation, which in turn can provide better living and working spaces for occupants.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Acronym	Description
CO_2	Carbon Dioxide
IEQ	Indoor Environmental Quality
HVAC	Heating, Ventilation, Air Conditioning
SBS	Sick Building Syndrome

BES	Building Energy Simulation
GUI	Graphical User Interface
AHU	Air Handling Unit
VAV	Variable Air Volume
CAV	Constant Air Volume
FCU	Fan Coil Unit
COP	Coefficient of Performance
ACH	Air Change per Hour
MPC	Model Predictive Control
RMSE	Root Mean Squared Error
CV RMSE	Coefficient of Variance of Root Mean Squared Error
MAE	Mean Absolute Error
EUI	Energy Use Intensity
HRV	Heat Recovery Ventilator
ERV	Energy Recovery Ventilator

Appendix A. On-Site Measurement Procedures and Comparison

Table A1. Measurements Result of the Classrooms Tested.

	RBB 2119	**ARC 108**	**ENG LG14**	**VIC 105**	**RBB 2147**	**ENG 106**	**KHE 221**	**RCC 204**	**RBB 2166**
Date of Testing	Jan.25	Jan.29	Jan.30	Jan.31	Feb.01	Feb.04	Feb.05	Feb.13	Feb.15
No. of Hours Tested	8	9	8	6	6	5	7	7	8
Capacity	90	170	160	120	135	90	120	20	200
Mechanical system	VAV	CAV	VAV	CAV	VAV	VAV	VAV	VAV	VAV
Indoor Temperature (°C)									
Average	23.5	23.6	23.7	21.5	23.1	22.9	23.7	22.4	23.2
Maximum	24.3	24.5	24.9	23.9	23.8	23.8	24.4	23.2	23.9
Minimum	22.7	21.8	22.1	20.6	22.5	21.7	21.6	21.4	22.3
Average Exterior Temperature (°C)	−6.5	6.3	−6.9	−5.9	−0.9	2.5	6	−5.2	−4.7
Thermostat Set point Temperature (°C)									
Heating cooling	21.2 23.5	21.7	22 24	22	21.2 23.5	21.2 23.5	22	22	21.2 23.5
Relative Humidity (%)									
Average	21	39	23	16	24	35	33	16	26
Maximum	16	42	27	31	28	39	39	20	28
Minimum	18	36	18	15	22	34	28	15	24
Average air velocity (m/s)	0.14	0.18	0.09	0.11	0.16	0.11	0.09	0.1	0.11
Carbon Dioxide (ppm)									
Average	584	1306	1005	933	566	791	1015	858	623
Maximum	699	1813	1244	1327	668	1097	1264	1245	764
Minimum	420	520	525	528	437	485	555	406	479
Thermal Sensation Ranges									
−5	9%	8%	1%	28%	2%	10%	7%%	8%	9%
0.09	68%	72%	80%	63%	73%	80%	81%%	76%	74%
2,3	23%	20%	19%	9%	25%	10%	12%	16%	17%
Satisfaction with Thermal Condition									
Satisfied	91%	55%	88%	58%	92%	81%	69%	80%	82%
Dissatisfied	9%	45%	12%	42%	8%	19%	31%	20%	18%
Satisfaction with Indoor Air Quality									
Satisfied	85%	48%	81%	64%	83%	80%	60%	73%	78%
Dissatisfied	15%	52%	19%	36%	17%	20%	40%	27%	22%
Average clo value	0.95	0.87	0.88	0.87	0,93	0.89	0.79	0.91	0.88

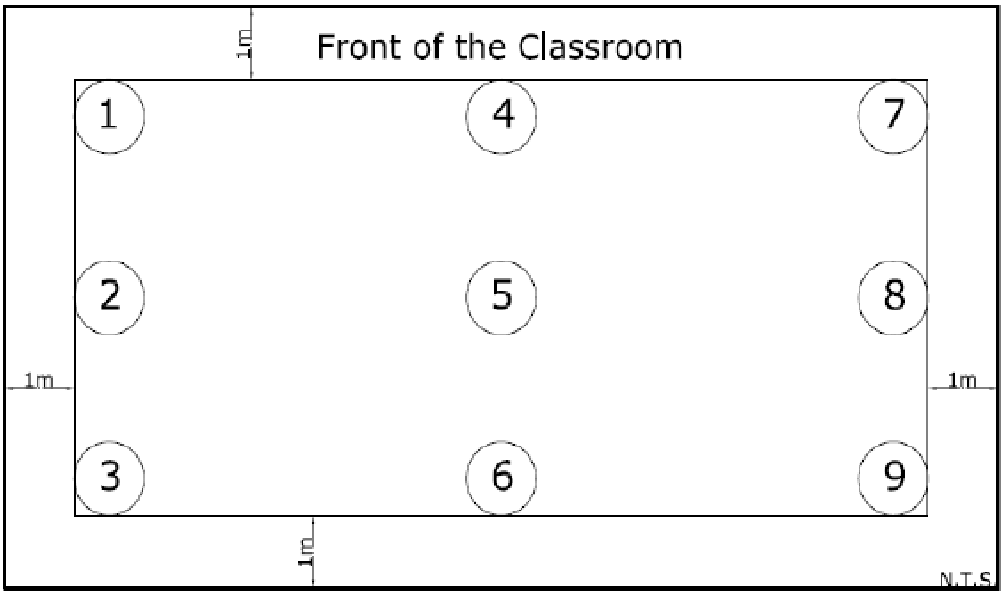
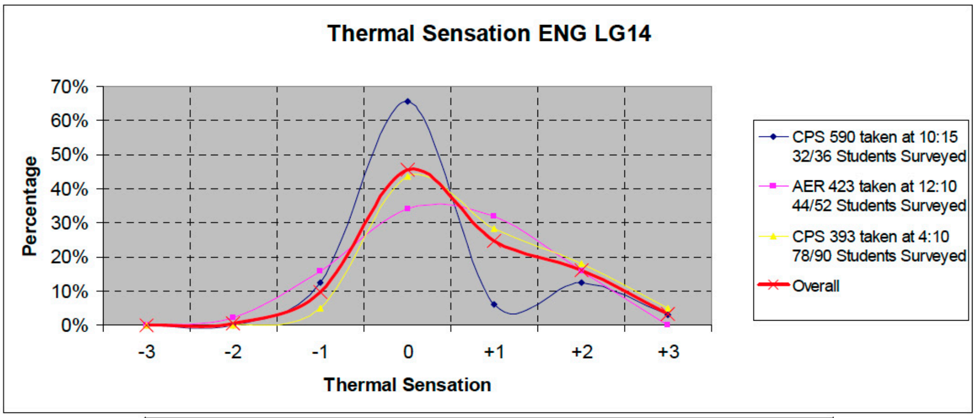


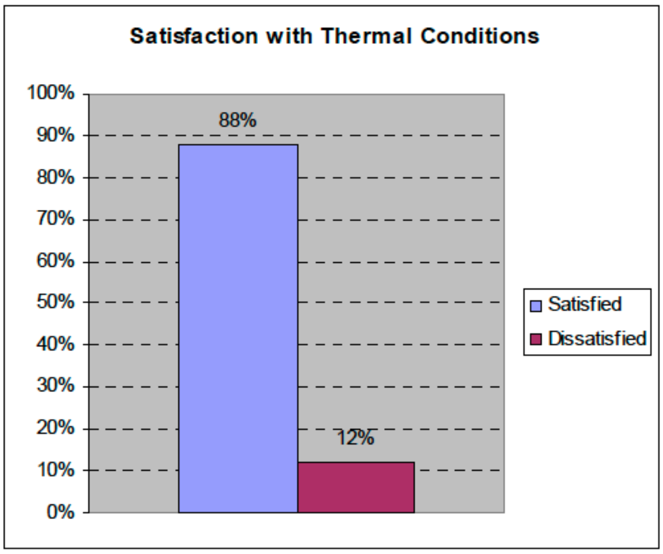
Figure A1. Plan Showing Dataloggers Placement Distribution Across the Classroom.

Appendix B. Questionnaire Results



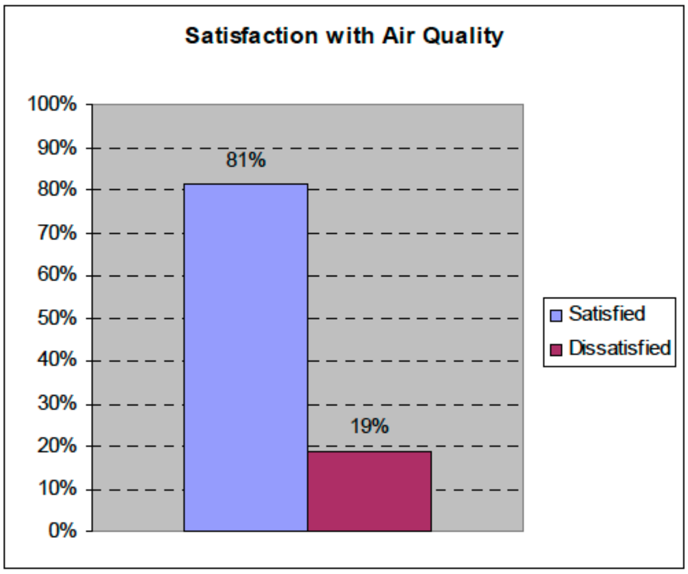
Thermal Sensation in ENG LG14				
Thermal Sensation	CPS 590	AER 423	CPS 393	Overall
+3-Hot	3.1%	0%	5.1%	3.2%
+2-Warm	12.5%	15.9%	17.9%	16.2%
+1-Slightly Warm	6.3%	31.8%	28.2%	24.7%
0-Neutral	65.6%	34.1%	43.6%	45.5%
-1-Slightly Cool	12.5%	15.9%	5.1%	9.7%
-2-Cool	0%	2.3%	0%	0.6%
-3-Cold	0%	0%	0%	0%
Percentage in acceptable range (-1 to +1)	84.4%	81.8%	76.9%	80%

Figure A2. Thermal Sensation Survey Results. Note that CPS 590, AER 423, and CPS 393 are lecture course codes respectively.



Satisfaction with thermal conditions in ENG LG14				
	CPS 590	AER 423	CPS 393	Overall
Satisfied	97%	86%	85%	88%
Dissatisfied	3%	14%	15%	12%

Figure A3. Thermal Satisfaction Survey Results.



Satisfaction with air quality in ENG LG14				
	CPS 590	AER 423	CPS 393	Overall
Satisfied	84%	77%	82%	81%
Dissatisfied	16%	23%	18%	19%

Figure A4. Air Quality Satisfaction Survey Results.

Appendix C. Classroom Lecture Schedules and Occupancy Pattern Input to Simulation

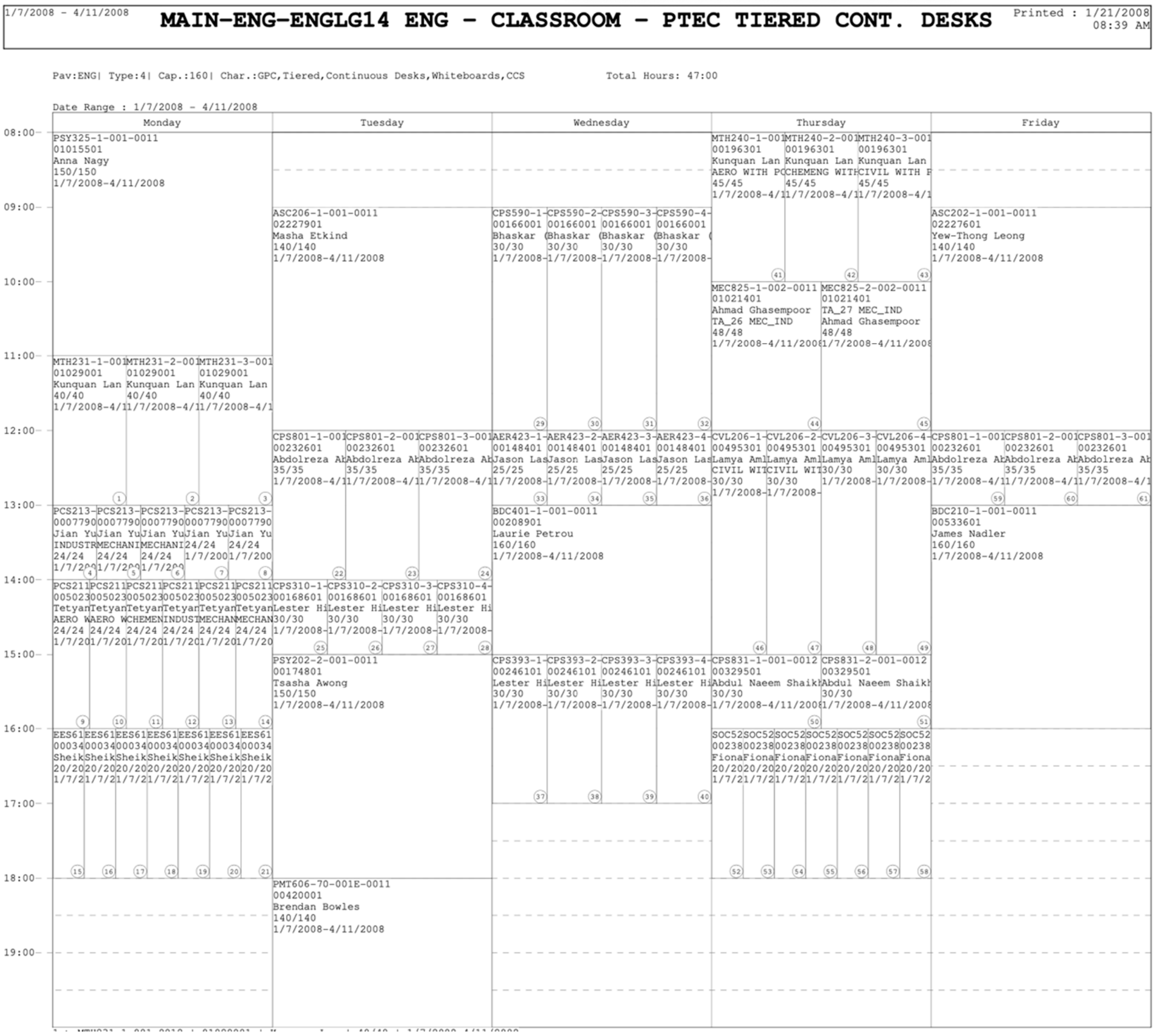


Figure A5. Weekly Lecture Schedule and Expected Occupant Numbers in the Classroom.

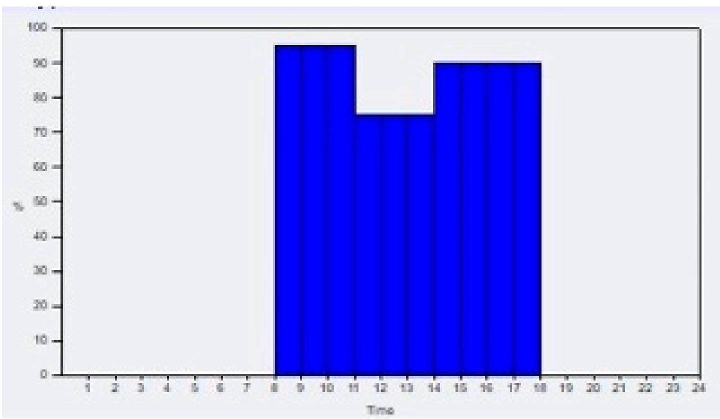


Figure A6. Monday Occupancy Pattern (input to BES).

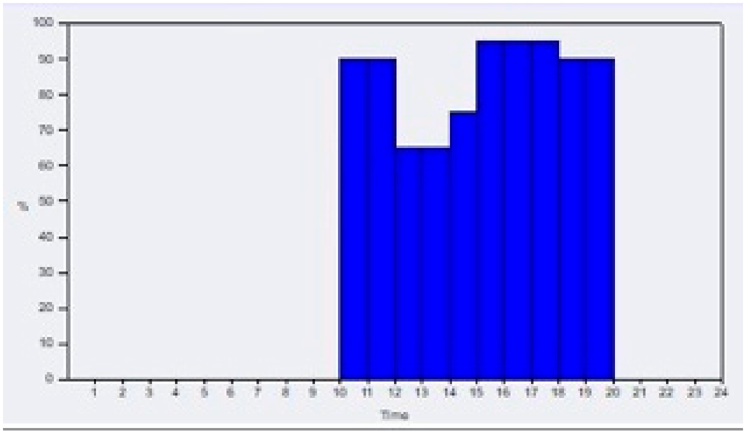


Figure A7. Tuesday Occupancy Pattern (input to BES).

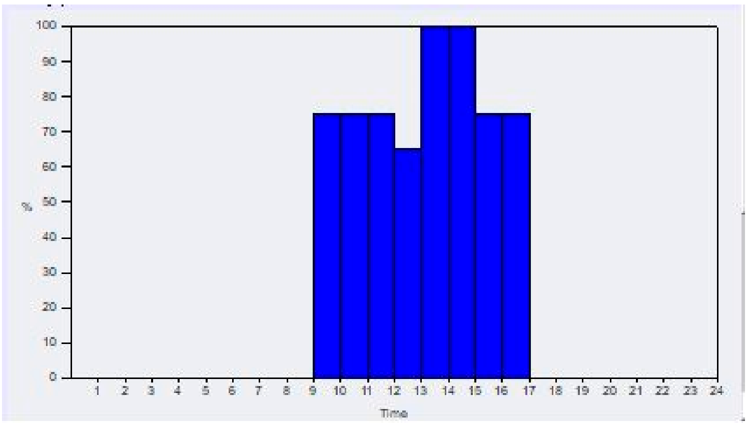


Figure A8. Wednesday Occupancy Pattern (input to BES).

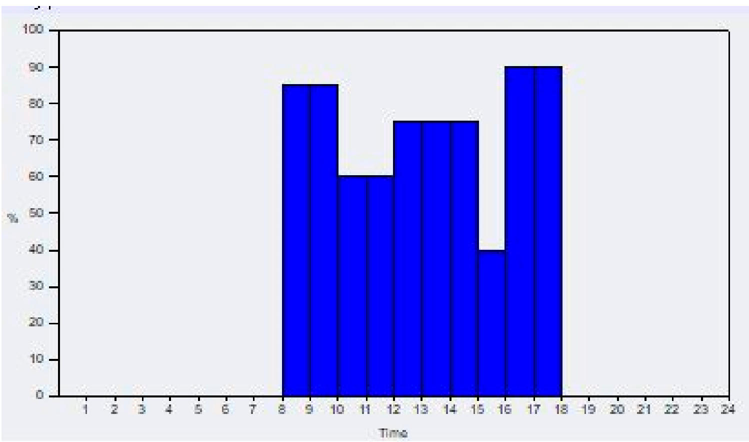


Figure A9. Thursday Occupancy Pattern (input to BES).

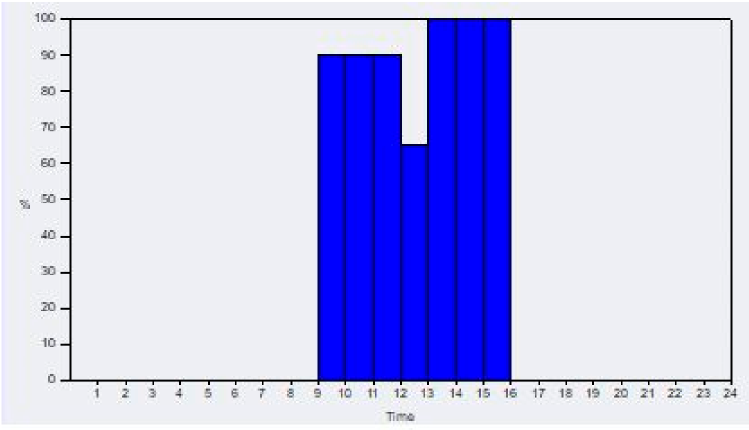


Figure A10. Friday Occupancy Pattern (input to BES).

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