AN ANALYSIS OF THERMAL COMFORT PERCEPTION IN CAL POLY’S
MATH & SCIENCE BUILDING

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ABSTRACT

An Analysis of Thermal Comfort Perception in Cal Poly’s Math & Science Building

Pouria Ali Fariborzi

Since Americans, on average, spend approximately 90% of their time indoors according to the EPA, it is crucial to provide room occupants with the best, most comfortable, and healthiest possible environment, which is known as Indoor Environmental Quality (IEQ). This thesis aims to identify how we can provide comfortable learning environments to improve student success. To determine the best possible environment for occupants, a model of the Math & Science Building was developed, validated, and modified using DesignBuilder. In addition, we compared thermal comfort surveys to actual measured conditions for some classrooms. Analysis indicates that students prefer a cooler thermal environment rather than a warmer thermal environment and that the Fanger PMV model is not as accurate as anticipated for predicting thermal comfort. Ventilation strategies could be modified to improve the indoor conditions, especially during exam times and in the afternoon when CO₂ is shown to be at the highest concentration.
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Chapter 1

Introduction and Background

1.1 Indoor Environmental Quality and its Importance

Americans, on average, spend approximately 90 percent of their time indoors, where the concentrations of some pollutants are often 2 to 5 times higher than typical outdoor concentrations. [1] Since so much time is spent indoors, whether that be in homes, offices, or classrooms—it is necessary to provide room occupants with the most comfortable and healthiest possible environment. The environment that occupants are subject to and how comfortable they feel is known as the Indoor Environmental Quality (IEQ). According to the CDC, IEQ refers to the quality of a building’s environment in relation to the health and wellbeing of those who occupy space within it. [2] IEQ includes four key factors: acoustics, lighting, indoor air quality, and thermal comfort. Since building occupant demographics consist of a wide variety of people ranging from young to old adults, some with disabilities, others with medical conditions, etc.—it is important to understand IEQ so that solutions can be developed that benefit everyone. The term "sick building syndrome" is used to describe situations in which building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified. [3] The complaints may be localized in a particular room or zone or may be widespread throughout the building. A 1984 World Health Organization Committee report suggested that up to 30 percent of new and remodeled buildings worldwide may be the subject of excessive complaints related to
indoor air quality (IAQ). [3] Indicators of sick building syndrome include headache; eye, nose, or throat irritation; dry cough; dry or itchy skin; dizziness and nausea; difficulty in concentrating; fatigue; and sensitivity to odors. [3] On the Cal Poly campus, improving IEQ is crucial to not only student health and academic success, but also to faculty wellbeing, given that students and faculty spend most of their day indoors on campus in a variety of locations. This thesis will focus on two aspects of IEQ and their influence on conditions in the classroom—thermal comfort and indoor air quality.

1.2 Thermal Comfort

As defined by ASHRAE Standard 55, thermal comfort is the “condition of mind that expresses satisfaction with the thermal environment.” [4] Thermal comfort is complex and difficult to evaluate because it is a combination of both psychological and physiological factors that can affect people differently. Since it is not possible to control psychological factors accurately, this thesis focuses on the physiological factors that influence thermal comfort, including humidity, air speed/temperature, radiant temperature, occupant metabolic rate, and occupant clothing insulation. In conditioned spaces, room air temperature and relative humidity control are found to have a greater effect on maintaining occupant thermal comfort than the other factors. [5] ASHRAE Standard 55 defines the necessary thermal environmental conditions for human occupancy and is used in industry to ensure thermal comfort needs are met when designing or retrofitting buildings for occupancy.
One of the most notable models for determining occupant thermal comfort was developed by P.O. Fanger. Fanger developed the model based on the research he performed at Kansas State University and the Technical University of Denmark. [6] Fanger used a seven-point form of a thermal sensation scale along with numerous experiments involving human subjects in various environments. He related the subjects in response to the variables, which influence the condition of thermal comfort. Fanger's model is based upon an energy analysis that considers all the modes of energy loss from the body, including: the convection and radiant heat loss from the outer surface of the clothing, the heat loss by water vapor diffusion through the skin, the heat loss by evaporation of sweat from the skin surface, the latent and dry respiration heat loss, and the heat transfer from the skin to the outer surface of the clothing. According to ISO 7730, PMV is calculated using the following 4 equations: [7]
\[ PMV = [0.303 \times e^{-0.036 M} + 0.028] \]

\[
\{ (M - W) - 3.05 \times 10^{-3} \times [5773 - 6.99 \times (M - W) - p_a] - 0.42 \times [(M - W) - 58.15]\}

\[
\{ -1.7 \times 10^{-5} \times M \times (5867 - p_a) - 0.0014 \times M \times (34 - t_a)\}

\[
\{-3.96 \times 10^{-8} \times f_{cl} \times [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \times h_c \times (t_{cl} - t_a)\}
\]

\[ t_{cl} = 35.7 - 0.028 \times (M - W) - l_{cl} \times \{3.96 \times 10^{-8} \times f_{cl} \times [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} \times h_c \times (t_{cl} - t_a)\} \]

\[ h_c = 2.38 \times |t_{cl} - t_a|^0.25 \text{ for } 2.38 \times |t_{cl} - t_a|^0.25 > 12.1 \sqrt{\bar{v}_{ar}} \]

\[ h_c = 12.1 \sqrt{\bar{v}_{ar}} \text{ for } 2.38 \times |t_{cl} - t_a|^0.25 < 12.1 \sqrt{\bar{v}_{ar}} \]

\[ f_{cl} = 1.00 + 1.290 l_{cl} \text{ for } l_{cl} \leq 0.078 \, m^2 \times \frac{K}{W} \]

\[ f_{cl} = 1.05 + 0.645 l_{cl} \text{ for } l_{cl} > 0.078 \, m^2 \times \frac{K}{W} \]
Where:

\( M \) is the metabolic rate, in \( W/m^2 \);

\( W \) is the effective mechanical power, in \( W/m^2 \);

\( I_{cl} \) is the clothing insulation, in \( m^2 * \frac{K}{W} \);

\( f_d \) is the clothing surface area factor;

\( t_a \) is the air temperature, in \( ^\circ C \);

\( \bar{t}_r \) is the mean radiant temperature, in \( ^\circ C \);

\( v_{ar} \) is the relative air velocity, in \( m/s \);

\( p_a \) is the water vapor partial pressure, in \( Pa \);

\( h_c \) is the convective heat transfer coefficient, in \( W/(m^2 * K) \);

\( t_d \) is the clothing surface temperature, in \( ^\circ C \);

The model assumes that the person is thermally at steady state with their environment. By determining the skin temperature and evaporative sweat rate that a thermally comfortable person would have in each set of conditions, the model calculates the energy loss. Then, using the thermal sensation votes from subjects at KSU and Denmark, Fanger created the Predicted Mean Vote (PMV) thermal sensation scale that is based on how the energy loss deviates from the metabolic rate. The sensation scale that Fanger used to calculate the PMV is as follows:

3 = hot
2 = warm
1 = slightly warm
0 = neutral
-1 = slightly cool
-2 = cool
-3 = cold
Fanger realized that the vote predicted was only the mean value to be expected from a group of people, and he extended the PMV to predict the Percentage of People who will be Dissatisfied (PPD) with the environment. [8] According to ISO 7730, PMV hard limits range from -2 to 2 while PPD ranges from 5% to 100%. PPD is calculated using the following equation: [7]

\[
PPD = 100 - 95 * e^{(-0.03353 * PMV^4 - 0.2179 * PMV^2)}
\]

ASHRAE Standard 55 states that acceptable PMV ranges from -0.7 to 0.7 for existing buildings and for PPD ranges from 5% to 20%. Figure 1.1 shows how PPD depends on PMV—the closer the PMV is to neutral, the lower the PPD. [6]

Figure 1.1 shows the relationship between PPD and PMV. It is evident that the larger the magnitude of PMV, whether positive or negative, the greater the PPD. Adapted from [6]
Fanger’s model is widely accepted for thermal comfort predictions, and there are web-based tools that use his model to predict thermal comfort with respect to ASHRAE Standard 55. The CBE Thermal Comfort Tool from UC Berkeley is one such tool that calculates and provides a visualization of acceptable comfort boundaries for occupants given a variety of inputs, which are based on ASHRAE Standard 55. [9] The inputs used for the CBE Thermal Comfort Tool’s calculations are the building’s operative temperature, air speed, relative humidity, as well as the occupants’ clothing insulations and metabolic rates. The operative temperature is the average between the air temperature and radiative temperature. The radiative temperature is the average temperature of all the surfaces (walls, ceilings, furniture) in a room. According to the CBE Thermal Comfort Tool, typical clothing insulations are: [9]

0.36 clo for walking shorts, short-sleeve shirt
0.50 clo for typical summer indoor clothing
0.54 clo for knee-length skirt, short-sleeve shirt, sandals, underwear
0.57 clo for trousers, short-sleeve shirt, socks, shoes, underwear
0.61 clo for trousers, long-sleeve shirt
0.67 clo for knee-length skirt, long-sleeve shirt, full slip
0.74 clo for sweatpants, long-sleeve sweatshirt
0.96 clo for jacket, trousers, long-sleeve shirt
1.0 clo for typical winter indoor clothing

Where 1.0 clo = 0.155 $\frac{K}{W} * m^2$

ASHRAE Standard 55 defines metabolic rate as the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface, expressed in met units, which are defined as 1 met = 58.2 $W/m^2$. [10] Table 1.1 below details a spectrum of activities and their respective metabolic rates. [11]
Table 1.1 lists metabolic rates for typical tasks, based on ASHRAE Standard 55. [11]

<table>
<thead>
<tr>
<th>Activity</th>
<th>Met Units</th>
<th>W/m²</th>
<th>(Btu/ft²)</th>
</tr>
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<tbody>
<tr>
<td><strong>Resting</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleeping</td>
<td>0.7</td>
<td>40</td>
<td>(13)</td>
</tr>
<tr>
<td>Reclining</td>
<td>0.8</td>
<td>45</td>
<td>(15)</td>
</tr>
<tr>
<td>Seated, quiet</td>
<td>1.0</td>
<td>60</td>
<td>(18)</td>
</tr>
<tr>
<td>Standing, relaxed</td>
<td>1.2</td>
<td>70</td>
<td>(22)</td>
</tr>
<tr>
<td><strong>Walking (on level surface)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9 m/s, 3.2 km/h, 2.0 mph</td>
<td>2.9</td>
<td>115</td>
<td>(37)</td>
</tr>
<tr>
<td>1.2 m/s, 4.3 km/h, 2.7 mph</td>
<td>2.6</td>
<td>150</td>
<td>(48)</td>
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<tr>
<td>1.8 m/s, 6.8 km/h, 4.2 mph</td>
<td>3.8</td>
<td>220</td>
<td>(70)</td>
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<td>55</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooking</td>
<td>1.6–2.0</td>
<td>95–115</td>
<td>(29–37)</td>
</tr>
<tr>
<td>House cleaning</td>
<td>2.0–3.4</td>
<td>115–200</td>
<td>(37–63)</td>
</tr>
<tr>
<td>Seated, heavy limb movement</td>
<td>2.2</td>
<td>130</td>
<td>(41)</td>
</tr>
<tr>
<td>Machine work</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sawing (table saw)</td>
<td>1.8</td>
<td>105</td>
<td>(33)</td>
</tr>
<tr>
<td>light (electrical industry)</td>
<td>2.0–2.4</td>
<td>115–140</td>
<td>(37–44)</td>
</tr>
<tr>
<td>heavy</td>
<td>4.0</td>
<td>235</td>
<td>(74)</td>
</tr>
<tr>
<td>Handling 50 kg (100 lb) bags</td>
<td>4.0</td>
<td>235</td>
<td>(74)</td>
</tr>
<tr>
<td>Pick and shovel work</td>
<td>4.0–4.8</td>
<td>235–280</td>
<td>(74–88)</td>
</tr>
<tr>
<td><strong>Miscellaneous Leisure Activities</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dancing, social</td>
<td>2.4–4.4</td>
<td>140–255</td>
<td>(44–81)</td>
</tr>
<tr>
<td>Calisthenics/exercise</td>
<td>3.0–4.0</td>
<td>175–235</td>
<td>(55–74)</td>
</tr>
<tr>
<td>Tennis, single</td>
<td>3.6–4.0</td>
<td>210–270</td>
<td>(66–74)</td>
</tr>
<tr>
<td>Basketball</td>
<td>5.0–7.6</td>
<td>290–440</td>
<td>(90–140)</td>
</tr>
<tr>
<td>Wrestling, competitive</td>
<td>7.0–8.7</td>
<td>410–505</td>
<td>(130–160)</td>
</tr>
</tbody>
</table>
The following eight figures show how the acceptable boundary—based on ASHRAE Standard 55 for thermal comfort—shifts as the input values for operative temperature, air speed, relative humidity, metabolic rates, and clothing insulations vary. The “blue zone” (comfort zone) is the defined thermal comfort area based on the inputs that are within 10% PPD and -0.5 to 0.5 PMV ranges. The red “bullseye” is the exact point of the inputs. Although the 5 inputs depend on each other, during simulation, the inputs that were found to have the greatest influence were the operative temperature and relative humidity. To most accurately analyze how the changes in input values influence the thermal comfort acceptance boundaries, the input values were altered to yield the best-case scenario for thermal comfort: PMV = 0 and PPD = 5%. All the input scenarios are listed in Table 1.2.

Table 1.2 Inputs to the CBE Thermal Comfort Tool to have PMV = 0 (Neutral) and 5% PPD

<table>
<thead>
<tr>
<th>Figure</th>
<th>Operative Temp (°F)</th>
<th>Air Speed (fpm)</th>
<th>Relative Humidity (%)</th>
<th>Metabolic Rate (met)</th>
<th>Clothing Level (clo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>77.5</td>
<td>0</td>
<td>50</td>
<td>1.0</td>
<td>0.61</td>
</tr>
<tr>
<td>1.3</td>
<td>77</td>
<td>19.7</td>
<td>69</td>
<td>1.0</td>
<td>0.61</td>
</tr>
<tr>
<td>1.4</td>
<td>79.5</td>
<td>11</td>
<td>64</td>
<td>1.0</td>
<td>0.36</td>
</tr>
<tr>
<td>1.5</td>
<td>73</td>
<td>0</td>
<td>62</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1.6</td>
<td>68.5</td>
<td>2</td>
<td>55</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>1.7</td>
<td>79.5</td>
<td>35</td>
<td>34</td>
<td>1.0</td>
<td>0.61</td>
</tr>
<tr>
<td>1.8</td>
<td>81.5</td>
<td>2</td>
<td>14</td>
<td>1.0</td>
<td>0.36</td>
</tr>
<tr>
<td>1.9</td>
<td>72.5</td>
<td>2</td>
<td>82</td>
<td>1.0</td>
<td>0.96</td>
</tr>
</tbody>
</table>

The figures below from the CBE tool provide excellent visualizations for how individual inputs cause the comfort zone and the red “bullseye” to shift. The comfort zone is affected by metabolic rate, clothing insulation, and airspeed, whereas the red “bullseye” is impacted by the operative temperature and the relative humidity. It can be
noted that for all the figures, metabolic rate remained unchanged at 1.0 met, given that is the metabolic rate for students who are quietly seated, reading, and taking notes, according to ASHRAE Standard 55, (see Table 1.1). Based on performed simulations, when the clothing insulation level is decreased, the comfort zone shifts towards higher temperatures, while high clothing insulation levels result in the comfort zone shifting towards lower temperatures. This makes sense because less clothing insulation means the occupants’ clothes do not retain heat and so the occupant would be more comfortable in a warmer environment; whereas higher clothing insulation means the occupants’ clothes retain heat and so the environment must be cooler so that the occupants do not overheat. As the airspeed is increased, the comfort zone shifts towards higher temperatures to compensate for the cooling effect that constant air supply has. On the other hand, a decrease in or absence of airspeed results in the comfort zone shifting towards lower temperatures. The red “bullseye” describes the PMV and PPD within the comfort zone. There are a variety of possible operative temperature and relative humidity values that can yield PMV = 0 and PPD = 5% in the same comfort zone. It can be concluded that a “happy middle” must be achieved by first establishing a comfort zone based on airspeed, occupant metabolic rate, and occupant clothing insulation while adjusting operative temperatures and relative humidity to fit within the comfort zone and yield the best possible PMV and PPD within the comfort zone.
Figure 1.2 shows the acceptable thermal comfort boundary given an operative temperature of 77.5 degrees Fahrenheit, airspeed of 0 feet per minute (fpm), relative humidity of 50%, metabolic rate of 1 met, and clothing insulation of 0.61 clo, which yield PMV = 0 and PPD = 5%.

Figure 1.3 shows the acceptable thermal comfort boundary given an operative temperature of 77 degrees Fahrenheit, airspeed of 19.7 fpm, relative humidity of 69%, metabolic rate of 1 met, and clothing insulation of 0.61 clo, which yield PMV = 0 and PPD = 5%.
Figure 1.4 shows the acceptable thermal comfort boundary given an operative temperature of 79.5 degrees Fahrenheit, airspeed of 11 fpm, relative humidity of 64%, metabolic rate of 1 met, and clothing insulation of 0.36 clo, which yield PMV = 0 and PPD = 5%.

Figure 1.5 shows the acceptable thermal comfort boundary given an operative temperature of 73 degrees Fahrenheit, airspeed of 0 fpm, relative humidity of 62%, metabolic rate of 1 met, and clothing insulation of 1.0 clo, which yield PMV = 0 and PPD = 5%.
Figure 1.6 shows the acceptable thermal comfort boundary given an operative temperature of 68.5 degrees Fahrenheit, airspeed of 2 fpm, relative humidity of 55%, metabolic rate of 1 met, and clothing insulation of 1.5 clo, which yield PMV = 0 and PPD = 5%.

Figure 1.7 shows the acceptable thermal comfort boundary given an operative temperature of 79.5 degrees Fahrenheit, airspeed of 35 fpm, relative humidity of 34%, metabolic rate of 1 met, and clothing insulation of 0.61 clo, which yield PMV = 0 and PPD = 5%.
Figure 1.8 shows the acceptable thermal comfort boundary given an operative temperature of 81.5 degrees Fahrenheit, airspeed of 2 fpm, relative humidity of 14%, metabolic rate of 1 met, and clothing insulation of 0.36 clo, which yield PMV = 0 and PPD = 5%.

Figure 1.9 shows the acceptable thermal comfort boundary given an operative temperature of 72.5 degrees Fahrenheit, airspeed of 2 fpm, relative humidity of 82%, metabolic rate of 1 met, and clothing insulation of 0.96 clo, which yield PMV = 0 and PPD = 5%.
1.3 Indoor Air Quality

Another key factor that influences IEQ is the Indoor Air Quality or IAQ, which is crucial for occupant health and wellbeing. Since people spend large amounts of time indoors, having clean air can lead to a higher quality of life and lower risk of transmitting/catching respiratory illnesses, which has been especially important during the COVID-19 pandemic. Humans exhale carbon dioxide and inhale oxygen, so it is important to maintain healthy room conditions by filtering the air so that air particles do not accumulate and progressively worsen IAQ and IEQ.

Pollutants are not just limited to carbon dioxide either, but include other common environmental pollutants such as radon, asbestos, mold, lead particles, and nitrogen dioxide. [12] Additional health effects that are associated with poor air quality include dizziness, headaches, fatigue, and sinus irritation, which can negatively impact students’ learning and success in classrooms. [13] Student learning and success is the ability for the students to concentrate well in class and to perform well on quizzes/exams so to receive a favorable grade in the course. The EPA suggests that poor air quality will affect student performance in classes by making it harder for them to concentrate in class and/or feel comfortable in class with the air quality. Not only do the side-effects of poor room conditions trouble occupants, but if students become sick and miss school, catching up on missed classwork can be difficult depending on the severity of the illness. In the case of COVID-19, Cal Poly students who test positive are out of the classroom for a minimum of 10 days for quarantine and longer if symptoms persist.
Factors that affect the room’s IAQ include the outdoor climate, weather conditions, and occupant behavior; however, the most important factor that influences IAQ is the room’s air exchange rate, which is the rate at which all the air in a room is replaced with fresh air from the outdoors. The outdoor air exchange rate is important in determining indoor pollutant concentrations and can be approximated based on the number of open windows/doors and openings/cracks in building construction that allow the air in the room to circulate and filter with air from outdoors. According to ASHRAE Standard 62.1, the required combined outdoor air rate for a lecture classroom and university laboratory are 8 cubic feet per minute (cfm) per person and 17 cfm per person respectively. The outdoor air rate for minimum ventilation is based on the occupant density, which in this case, for the given outdoor air rate requirements are 65 occupants per 1,000 square feet and 25 occupants per 1,000 square feet for a lecture classroom and university laboratory respectively. [14]

Occupant activity is predicted to be very minimal since students are seated, taking notes, or writing an exam, and therefore, breathing at a normal/resting rate. For decades, researchers have agreed that infectious people exhale airborne viruses at the same time as they exhale CO₂. [15] Carbon dioxide is one of the biggest contaminants of shared spaces like classrooms. One of the main ways that CO₂ is measured is with a Nondispersive Infrared Sensor (NDIR), which calculates contamination concentrations by using the property that CO₂ absorb infrared rays. A NDIR CO₂ sensor has an infrared light emitter that emits infrared light and an infrared sensor that detects infrared light. [15]
Since the CO₂ levels in a classroom increase with the number of occupants, it is reasonable to assume that the risk of transmitting airborne viruses increases with higher levels of CO₂ in an indoor environment. Although this is an undeniably problematic fact, the transmission risk of an airborne virus can be reduced if CO₂ thresholds are maintained. [16] Thresholds are influenced by clean air standards, which states that the typical amount of CO₂ present in the outdoors is roughly 400 ppm for clean air conditions. [17] It has been found that indoors, any concentration of CO₂ higher than 1,000 ppm is considered unacceptable, since contamination levels that high are dangerous to occupants by putting them at higher risk of transmitting/catching airborne viruses. [17]

Cal Poly’s minimum ventilation requirements are based on both room square footage and number of occupants, as mandated by ASHRAE Standard 62.1. [14] The ventilation rate required to control both people-related sources, which is denoted as \( V_p \), and building-related or area-based sources, denoted as \( V_a \), is the sum of the ventilation required to control each of them alone at the breathing zone, \( V_{bz} \), which is the breathing zone ventilation rate value is calculated using the following equation:

\[
V_{bz} = V_p + V_a
\]

ASHRAE Standard 62.1 defines breathing zone as the region within an occupied space between 3 and 6 feet above the floor and more than 2 feet from walls or fixed air-conditioning equipment. [11] As reference, the breathing zone can be visualized with the figure below. [14]
Figure 1.10 The breathing zone is shown as a specific, mathematically calculated perimeter encapsulated by a larger, occupied space. Adapted from [14].

If it is assumed that the occupant component is proportional to the number of people and the building area component is proportional to the building area, the additivity concept for the ventilation required in the breathing zone of a space can be expressed by the following equation:

\[ V_{bz} = R_p P_Z + R_a A_Z \]

Where \( R_p \) is the outdoor airflow rate required per person, \( P_Z \) is the number of people in the ventilation zone during typical usage, \( R_a \) is the outdoor airflow rate required per unit area, and \( A_Z \) is the net occupiable floor area of the ventilation zone in ft\(^2\). Based on ASHRAE Standard 62.1 Table 6A, the ventilation rate required per person, \( R_p \), must be at least 5 cfm and the ventilation rate required per unit area, \( R_a \), must be at least 0.06 cfm/ft\(^2\) for low activity environments like classrooms or offices. [14] It is assumed that Cal Poly is following the recommended minimum outdoor airflow rate required per person and the recommended outdoor airflow rate required per unit area.
1.4 Previous Studies on Thermal Comfort in Higher Education

The following is a brief review of research done in academic settings for thermal comfort and IAQ.

Primary and secondary students in Australia (K-12, ages 6-18) during the summer season (20°C-35°C) prefer temperatures 2-3K cooler than the neutrality predicted for adults of the same thermal environment. The 2-3K difference refers to the ASHRAE 55 adaptive model for Thermal Sensation Vote (TSV) Air conditioning methods, windows, fans, blinds, adjusting clothing among favorites for thermoregulation in children. [18]

A 2016 by Yan et. al. on thermal comfort expectations and adaptive behavioral characteristics showed that the outdoor climate has an influence on thermal adaptability, and therefore, the neutral temperature in winter is lower than that in spring. The outdoor temperature affected the adaptive behavior of elementary and high school students, even in heated buildings. Since the lower the outdoor temperature was, the higher the indoor heating temperature was, overheating indoor temperature led to less clothing and more likelihood of window–opening, and thus caused more energy consumption. The lower the outdoor temperature was, there was a stronger the dependence on heating equipment, acceptability of high temperature, and impatience with the low temperature environment. [19]

When looking into the perceptions of specific groups and sectors, thermal comfort studies focus on businesses and companies, seeming to disregard academia entirely. [20] Many studies that are performed through an education-lens have been done with young
students in K-12 courses. [21] These classes are mandated education that set a different bar for success and performance compared to the opt-in nature of higher education. These studies, however, can be used to motivate and inform studies on academic performance in university settings. For example, Wargocki and Wyon conclude the poor indoor environments can reduce children’s performance by as much as 30% and providing a better thermal environment would be cost effective. [22] In addition, a 2013 study using university students revealed that learning and motivation is affected by temperature. [23]

A 2021 survey of student at Cal Poly found that for lectures, after the room being quiet, the most important feature for full classrooms was windows rather than air conditioning, while for exams, air conditioning was ranked more important than windows. In quiet, half-filled classrooms, it was split evenly between windows and air conditioning for exams, but for lectures, windows were more important than air conditioning. These results for ideal classroom conditions matches what students rated as important for study locations—natural light and windows. [24] We know that access to windows and daylight is associated with lower prevalence of ‘sick building syndrome’ and it is the same for students in classrooms, even if they are only in that specific room for one to two hours at a time. [25]

Schweiker et. al. collected data from 47 participants to conduct a detailed study on their expectations on thermal perception. Participants were required to complete questionnaires throughout the day of their study to compare participants expectations of thermal comfort with the thermal comfort standards in Germany at the time. They found that “people have a wide range of expectations to indoor conditions...if expectations of
the indoor thermal conditions are not met, thermal comfort decreases.” [26] Additionally, they concluded that further research is necessary to conclude the correlation between the expectation of stable thermal conditions in unknown environments, such as laboratories.

Dan Caroll for Carnegie Mellon University discusses the topic of thermal comfort and CMU’s growing interest for the topic in his article from 2020. Caroll describes how Mario Berges, a professor of civil and environmental engineering at CMU, alongside his colleagues, have created a model that “combines environmental information with data on an individual’s body shape to determine at what temperatures that person will feel most comfortable.” [27] With this technology at hand, Berges and his colleagues can see the physiological and psychological effects that thermal comforts have on an individual’s health and day to day performance. The model, named OccuTherm “works by estimating the circumference of an individual’s shoulders from above, then combining it with height and weight estimates to infer the optimal temperature for that individual’s comfort”. [27] At the time of publication, OccuTherm has been deemed to be six percent more effective than any other approach in the industry and its accessibility by not having to ask for continual user feedback keeps the system accommodating and efficient at data collection. [27]

Occupancy and their activity levels negatively impact the room conditions. Carbon dioxide levels in the classroom have been shown to be directly related to a student’s alertness and ability to concentrate. High levels of carbon dioxide indicate a lack of fresh air intake and that negatively affects the health, attendance rate and learning
ability of students. [3] The accepted standard CO₂ level in a classroom is 1,000 ppm. That level is easy to maintain when a classroom is empty. Fill the classroom up with students and the level of can CO₂ rise. That is because carbon dioxide makes up a part of every breath you exhale causing the levels to rise as more people gather. While classrooms are a low-activity level environment, there will be a lower CO₂ transmission rate than a gym, for example, having too much CO₂ accumulate in a space like a classroom can affect student learning, according to The Energy Alliance Group of North America. [28]

1.5 Thesis Objectives and Chapter Summaries

The purpose of this thesis project is to determine the current indoor conditions in Cal Poly's Math and Science Building (Building 38) and make recommendations to improve the thermal comfort and indoor air quality using the current ventilation system installed in the building. To accomplish this purpose, the following tasks were completed.

The first step was to develop an accurate and validated model of Building 38 using DesignBuilder to evaluate student thermal comfort in classrooms and analyze how outdoor weather conditions and room occupancy affect room conditions. The building modeling software DesignBuilder enables users to create accurate building models and run simulations to obtain data on temperature, relative humidity, CO₂ levels, HVAC system outputs, and more. The model was validated using measured room data from rooms in the building. Using the validated model, we will show how different ventilation strategies and affect the IEQ and thermal comfort.
Second, we will show the analysis of pre-COVID data from SIEMENS’ Building Automation System (BAS) in the Cal Poly HVAC systems compared to the post-COVID yielded data from SIEMENS’ BAS in Building 38’s HVAC system to establish differences in HVAC operations once students returned to campus. In addition, actual room conditions will be shown, including CO$_2$ concentration and temperature. Recommendations to improve IEQ were made based on the data collected during this step.

Finally, short surveys were given to students in Building 38 to collect data on their feedback about their experiences and thermal comfort during classes. By utilizing the expected thermal comfort data for occupants and the actual thermal comfort data for occupants found from the surveys, the two were compared to understand the discrepancies between what occupants actually felt compared to predicted occupants’ sensation with regards to indoor air temperature and relative humidity.

Using the results of the current conditions in Building 38, the final objectives are to provide short-term affordable solutions to improve IEQ and long-term solutions for Cal Poly to implement to improve IEQ. This thesis work is completed as part of the larger research program led by Dr. Mott, whose goals include increasing thermal comfort satisfaction through crowd sourced data and developing mobile and web-based tools to track campus thermal comfort and improving student success by providing comfortable learning environments and reducing building energy usage on Cal Poly’s campus.

The following is a summary overview of the thesis report. Chapter 1 provided an introduction and background to IEQ, IAQ, and thermal comfort. Additionally, Chapter 1
referenced literature reviews of previous research done on thermal comfort in higher education to provide more insight on the purpose of this thesis. Chapter 2 gives a detailed description of Building 38, with respect to its location, building layout, and HVAC system. Chapter 3 outlines the methods used to develop and validate an accurate model of Building 38. Chapter 4 details the results that were yielded during the various modeling simulations. Simulations include occupied model comparisons for case study rooms, pre and post COVID-19 operating conditions, as well as preferred thermal conditions gathered from student surveys. Finally, Chapter 5 summaries conclusions that can be drawn from the results yielded in Chapter 4 and recommendation for future work to continue this research.
Chapter 2

Cal Poly’s Math and Science Building

Chapter 2 describes Building 38—Cal Poly’s Math and Science Building. The location is described—including the is the local climate in San Luis Obispo, California and building location on the California Polytechnic State University campus. The building construction, floorplan layout and orientation are then detailed. Lastly, the AHUs used in the building’s HVAC system are described, as well as the specific zones for the different AHUs operate.

2.1 Location

San Luis Obispo is located on the central coast of California, approximately the halfway point between Los Angeles and San Francisco. With such a unique location comes similarly unique weather—San Luis Obispo’s cool Mediterranean climate could be best described as a combination of Southern California’s warm and dry climate and Northern California’s cold and wet climate. San Luis Obispo is in ASHRAE climate zone 3C [29] or Köppen-Geiger climate classification, Csb, and the climate is classified as warm temperate having warm, dry summers. [30] Building 38, the Math and Science Building, as shown in Figure 2.1, is in the center of California Polytechnic State University’s campus in San Luis Obispo and is one of the most frequented buildings among students of all majors and levels. The Math and Science building is composed of primarily classrooms and computer labs, with some space reserved for faculty offices, making it used for a variety of reasons such as attending meetings, office hours, class, or study sessions.
2.1 Location of Building 38 respective to campus. The building is circled in red and is bordered by N. Perimeter road on the North side and walking paths on the East and South ends. There is a small staff and visitor parking lot on the West Side.

2.2 Building Layout

The concrete-built structure sits partly up a slope, very tightly surrounded by a large hedge and dozens of large trees that cast significant amounts of shade to cool Building 38, which can be seen in the figures below. The buildings next to Building 38 are of similar size and do not shade the building. The Math and Science Building is composed of two sections—the science wing and the math wing, as denoted in the figures.
Since Building 38 has 12 total walls and thus a complex shape, Figure 2.2 shows detail in the building footprint and indicates the building’s orientation. The areas of both the science wing and math wing are approximately 16,000 square feet each, not accounting for the middle hallway that connects the two wings. The blue arrow on the compass axis indicates the true orientation of the science wing of Building 38 respective to North, represented by the Greek symbol, theta, which is approximately 11 degrees per the architect’s plans.

Figure 2.2 Building 38’s orientation, captured from Google Maps Satellite view.

The math wing consists of two building levels and most of the wing sits along or atop the slope (as shown in Figures 2.3 and 2.4), whereas the science wing consists of a ground
floor at ground level. Figures 2.5 and 2.6 show the floorplans for the first and second floors for Building 38 with the math and science wings denoted. The colors indicate offices and meeting spaces (red), or classrooms (green/yellow).

Figure 2.3 One of the walls of Building 38’s math wing that sits atop a slope. The picture was taken from the brick walkway that divides Building 38 and Building 20. To the west of the wall is the first-floor entrance to Building 38’s math wing and to the east is the second-floor entrance to Building 38’s math wing.
Figure 2.4 shows the wall of the math wing parallel to the wall shown in Figure 2.3. Here it can also be seen that the math wing sits atop a slope, surrounded by trees that cast shade on the building. While the view of the first floor is mostly covered from the angle this picture was taken from, the window for the first floor can be seen, which has been indicated.
Figure 2.5 The floorplan for the first level of Building 38.
2.3 HVAC System

The Math and Science Building’s HVAC systems are composed of 6 total air handling units (AHUs) that regulate the indoor room conditions. Of the 6 AHUs, AHU-1 and AHU-2 are the systems that service most rooms in the building. AHUs 3-6, service one room each. Not all the HVAC systems serve the same function—for example, AHU-1 and AHU-2 supply only heating while AHU-3, AHU-4, AHU-5, and AHU-6 supply both heating and cooling. Figures 2.7 and 2.8 show which AHUs service which rooms. AHU-2 operates exclusively in the math wing—both the first and second floors. The science wing is serviced primarily by AHU-1; however, a few larger labs/classrooms have individual AHUs as shown in Figure 2.7. Figure 2.8 also shows the approximate location of the AHUs on the roof of the science wing.
Figure 2.7 Building 38 first level HVAC system floorplan layout. AHU-2 operates exclusively in the math wing. The science wing is powered primarily by AHU-1; however, a few larger labs/classrooms have individual AHUs, being AHU-3, AHU-4, AHU-5, and AHU-6.
Figure 2.8 Building 38 second level HVAC system floorplan layout. Since the second level consists of only the math wing, the only HVAC AHU that operates on the second level is AHU-2.
Like all Cal Poly buildings, Building 38’s HVAC systems are controlled by SIEMENS’ BAS. Figure 2.9 shows an example of the Graphical User Interface (GUI) to monitor and control AHU-1. AHU-1 services solely the science wing of the building while AHU-2 services both the first and second floors of the math wing (as shown in Figure 2.7 and Figure 2.8). The SIEMENS screen below shows the control system for the AHU and the many operative parts it has, as well as the location of temperature sensors. The outside damper present in the system controls the amount of outside air that circulates into the HVAC system based on how open the damper is. The outside air mixes with the return air of the system and results in the mixed air that is supplied to the rooms. Mixed air is then passed through a centrifugal fan. The AHU’s fan is controlled using a Variable Frequency Drive, which allows the control of the fan speed to meet building ventilation requirements. Since this AHU has no cooling and only heating, it makes sense that in the bottom right corner of the screenshot, only a heating coil is found, which heats the mixed air. Ultimately, the heated mixed air is then supplied (SA) to the building and comes back to the HVAC system as return air (RA) and continues this cycle.

In the science wing, AHU-1 conditions about 10,000 square feet of the approximated total 16,000 square feet of the science wing, while AHU-2 conditions about 14,500 square feet of the approximated total 16,000 square feet of the math wing. The remaining HVAC systems, AHU-3, AHU-4, AHU-5, and AHU-6 cover the following amounts of floor area respectively: 1,400 square feet, 1,533 square feet, 1,532 square feet, and 1,529 square feet. AHU-1 and AHU-2 account for about 24,500 of the 32,000 square feet of Building 38—meaning that about 76.5% of the building’s room conditions are reliant
on these two HVAC systems. Therefore, AHU-1 and AHU-2 play a crucial role maintaining room conditions for occupants for most of Building 38.

Figure 2.9 SIEMENS AHU-1 HVAC GUI example. The main focuses for the HVAC systems were the return air temperature, damper opening percent, mixed air temperature, and whether the system had heating and/or cooling.
Chapter 3

Methods

Chapter 3 provides a summary of the methods used to develop and validate accurate models of Building 38. A description is given of the software, DesignBuilder, which was used to model Building 38 and its contents. Details of the model are described, including what resources were used to develop the model, as well as the parameters used in DesignBuilder. Room condition measurements were gathered with sensors to aid in the accurate development of the model by ensuring that collected measurements were as close as possible to simulated measurements. The model was validated by comparing simulated and collected data for unoccupancy for the building. Excel and MATLAB were used to assist with data analysis and visualization of results. The SIEMENS building data was provided to show the information that is yielded from AHU-2. Finally, thermal comfort surveys were gathered to determine the actual conditions felt by students and comparing them to simulated conditions.

The modeling was used to match measured data for Building 38 during unoccupancy and understand the discrepancies between how the model predicted students to feel and how surveys reflected student comfort. The main goal of the modeling portion was to eventually inform useful changes to the building environment, which were gathered by survey results. Once an accurate baseline was established, ventilation strategies were explored to reduce the room air temperature of the model that otherwise could not be done in real conditions with students. These ventilation
strategies were explored to understand how room air temperature could be reduced and thus influence thermal comfort of occupants.

3.1 DesignBuilder Modeling Software Description

DesignBuilder is an easy-to-use, EnergyPlus based software tool used to model energy, carbon, lighting, and comfort measurement and control. DesignBuilder was developed to make the building simulation process simpler. DesignBuilder compares alternative building designs by using function and performance-based method of comparison results by the various analyzes in a quick and economic manner.

DesignBuilder combines fast three-dimensional building modeling with dynamic energy simulations making it unique and the program needed to both “build up” or construct the building and model using one platform. Thanks to this feature, it is regarded as a unique software tool to create and evaluate building designs. It has specially developed modules that can be used effectively at any stage of the design process. With just a few parameters set, there is a wide range of opportunity to create a detailed design of the design. Its innovative productivity features allow even complex buildings to be modelled rapidly by non-expert users. [31]

DesignBuilder was developed to be used by a wide range of professionals such as architects, engineers, building services workers, energy consultants and related departments of universities. Some typical usage purposes are: [31]

- Evaluate options in terms of overheating, energy consumption and shading parameters.
• Evaluate the optimum use of daylight, including lighting control systems modeling to determine the savings rate in the corresponding electricity.

• Calculate the air temperature, velocity, and pressure distribution in or around the building by using the CFD (Computational Fluid Dynamics) module.

• Visualize the site plan and shading.

• Thermal simulation in buildings which are ventilated using natural ventilation.

• Determine the capacity of heating and cooling equipment needed for HVAC design.

DesignBuilder allows complex buildings to be modeled in a simple fast way even by non-expert users and is the first and most comprehensive program that creates a graphical interface to a EnergyPlus dynamic thermal simulation engine. This graphical interface makes the design of the buildings, their energy performance and CFD simulations allow to be displayed in 3D to provide support for further analysis. DesignBuilder uses the latest version of EnergyPlus simulation engine for calculating the energy performance of buildings. The resulting data can be filtered as desired and presented in graphs or can be exported in tabular format for use in other applications.

EnergyPlus is the most comprehensive building energy simulation program developed by the US Department of Energy, to model building heating, cooling, lighting, ventilation, and other energy flow, which has been constantly being improved. It is built on BLAST and DOE-2’s most popular features and capabilities, but at the same time it has many innovative features such as less than an hour simulation time, heat transfer
balance-based zone simulation, multi zone air conditioning system, thermal comfort and photo-voltaic systems. [31]

3.2 Building 38 Model Details

A model for Building 38 was created in DesignBuilder using the original construction drawings provided by Cal Poly facilities, measuring parameters in the building, and pictures of the outside to resemble the real conditions as closely as possible. The model was validated by comparing simulated room data against collected room data for unoccupied rooms: 148, 219, 220, and 226. By validating the model for unoccupied times, occupants can be added to the model to test different ventilation strategies. The idea is that since the indoor conditions from room to room are the same, then an accurate model for the entire building can be developed by validating data from rooms 148, 219, 220, and 226. This assumption is made that the adjacent rooms and hallways are maintained at the same conditions so there would be negligible heat transfer between the walls. The rooms chosen for the model validation represent four unique areas in the building, e.g., first and second floor, north and south facing. Using measured room data condition from the Fall 2021 term (rooms occupied), results of the model and actual indoor conditions will be gathered. The model was also used to determine which parameters have the largest impact on the indoor conditions.

To simulate the building as accurately as possible, the local weather data was uploaded into DesignBuilder from the San Luis Obispo weather station located on Cal Poly’s campus. The exact weather data is preferred over the default
data DesignBuilder offers for the San Luis Obispo region, because the default weather data in DesignBuilder’s database is outdated and does not accurately reflect the current weather conditions in San Luis Obispo. The weather information was sourced for the unoccupied modeling of rooms 148, 219, 220, and 226, which were each developed individually.

Referencing construction plans to develop an accurate model is extremely detail-oriented work. All pertinent building and room dimensions as well as general building materials for the walls and floors are determined from the Architect’s Original Construction Plans. [32] Since Cal Poly has slightly renovated the building since its construction, to ensure that proper dimensions are allocated to the correct rooms, the architect’s plans were cross referenced with the Cal Poly Floor Plans, shown in Figure 2.5 through Figure 2.8. If nearby trees or buildings cast shade on the room, the trees were integrated into the model using a simple component block. Figure 3.1 is a screenshot of the Building 38 model without any shade-casting trees or buildings.

![Figure 3.1 Model of Building 38 developed using DesignBuilder.](image)

The model in Figure 3.1 is shown in three different colors: green, white, and blue. The green color represents the building’s external walls, white represents the building’s windows, while blue is used to distinguish the doors from the walls and windows. Since the windows and doors are the only components of the building that can open and are
not air-sealed tightly when closed, it is safe to assume that due to heat transfer and mass conservation, outside air will leak into the building and affect the indoor room conditions, even when the windows and doors are closed. The air leakage is accounted for in the model using air infiltration, which is measured in air changes per hour. It is important to note that the outdoor air temperature plays a crucial role affecting the IEQ, since the building HVAC systems regulate indoor conditions based on outdoor conditions and return air temperatures. According to email exchanges with Cal Poly facilities, since classes on campus are held from 7 AM to 10 PM, and the HVAC system is on during these hours to resemble actual room conditions as accurately as possible. For the occupancy modeling, the lighting used the same schedule as the ventilation and heating. The schedule for occupants in a room is 7 AM – 10 PM, Monday – Friday. Full occupancy is defined as 35 people, met of 0.9, summer clothing is 0.5 clo, winter clothing is 1.0 clo, and CO2 generation rate is \(23.7 \times 10^{-6} \text{ ft}^3/\text{min}\). Specific details for the model are presented in Appendix A.

3.3 Room Condition Measurements

Room conditions were recorded/measured using the HOBO MX CO2 Logger devices, shown in Figure 3.2. The device can be easily attached to the wall in a room using removable command strips and is unobtrusive. The display screen can be turned off as well. Each of the devices recorded the air temperature, relative humidity, and CO2 concentration every five minutes. At the end of the collection period, the device was removed from the room and the data downloaded from the device using the HOBOware software.
The HOBO MX CO₂ Logger Device used for room data collection is versatile. It displays the CO₂ concentration in ppm, air temperature in Fahrenheit, and the relative humidity in percent. The versatility of the device made it easier to measure the most influential factors to thermal comfort (air temperature and relative humidity) and IAQ for individual classrooms in Building 38. The HOBO MX CO₂ Logger’s temperature sensor has a measurement range of 32° - 122°F, and a ±0.38 °F accuracy within that range. The relative humidity sensor has an accuracy of ±2% (maximum of 4.5%) from 20% - 80% relative humidity. Outside of that range, its accuracy is typically ±6%. The CO₂ sensor has a collection range of 0 to 5,000 ppm with an accuracy of ±50 ppm. [33] The device will also self-calibrate the CO₂ sensor once a week on auto-calibrate mode, or the user can calibrate the device on demand. The devices were temporarily secured to the wall next to the thermostat in each room, which are typically located next to the door, level with occupants sitting at desks, as shown in Figure 3.3. CO₂ is uniformly distributed throughout the room, so any location is for the sensors to be placed is acceptable—not just next to
the door. The rationale behind placing the CO₂ sensors here is to be at the breathing level of occupants to best capture their CO₂ emissions. Table 3.1 lists the classrooms in which we measured the conditions, the dates measured and occupancy status. The collected unoccupied data for the rooms were compared to the simulated data from DesignBuilder, which is shown in the Model Validation Section 3.4. The occupied room data for classrooms not in Building 38, i.e., 20-129, 33-286, and 02-203 correspond to times for which surveys were given to the students about their thermal comfort are described in Section 4.2.
Table 3.1 The buildings, rooms, and respective schedules that data was recorded for using the CO₂ Logger Device.

<table>
<thead>
<tr>
<th>Building-Room</th>
<th>Collection Start Date/Time</th>
<th>Collection End Date/Time</th>
<th>Occupied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>38-148</td>
<td>06/09/20: 9:00 AM</td>
<td>06/18/20: 2:00 PM</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>10/28/21: 12:00 PM</td>
<td>10/28/21: 1:00 PM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>10/29/21: 9:00 AM</td>
<td>10/29/21: 11:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>11/1/21: 8:00 AM</td>
<td>11/1/21: 9:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>11/1/21: 11:00 AM</td>
<td>11/1/21: 12:00 PM</td>
<td>Yes</td>
</tr>
<tr>
<td>38-219</td>
<td>06/09/20: 9:00 AM</td>
<td>06/18/20: 2:00 PM</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>10/29/21: 2:00 PM</td>
<td>10/29/21: 3:00 PM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>11/8/21: 7:00 AM</td>
<td>11/8/21: 8:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td>38-220</td>
<td>06/09/20: 9:00 AM</td>
<td>06/18/20: 2:00 PM</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>10/11/21: 9:00 AM</td>
<td>10/11/21: 10:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>10/28/21: 10:00 AM</td>
<td>10/28/21: 12:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>10/28/21: 1:00 PM</td>
<td>10/28/21: 3:00 PM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>10/29/21: 11:00 AM</td>
<td>10/29/21: 12:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>11/1/21: 7:00 AM</td>
<td>11/1/21: 8:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td>38-226</td>
<td>06/09/20: 9:00 AM</td>
<td>06/18/20: 2:00 PM</td>
<td>No</td>
</tr>
<tr>
<td>20-129</td>
<td>10/20/21: 10:00 AM</td>
<td>10/20/21: 12:00 PM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>10/22/21: 9:00 AM</td>
<td>10/22/21: 10:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>11/10/21: 9:00 AM</td>
<td>11/10/21: 10:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>11/12/21: 9:00 AM</td>
<td>11/12/21: 10:00 AM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>11/17/21: 10:00 AM</td>
<td>11/17/21: 12:00 PM</td>
<td>Yes</td>
</tr>
<tr>
<td>33-286</td>
<td>10/15/21: 12:00 PM</td>
<td>10/15/21: 4:00 PM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>11/19/21: 12:00 PM</td>
<td>11/19/21: 4:00 PM</td>
<td>Yes</td>
</tr>
<tr>
<td>02-203</td>
<td>10/4/21: 4:00 PM</td>
<td>10/4/21: 5:30 PM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>10/6/21: 4:00 PM</td>
<td>10/6/21: 5:30 PM</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>10/18/21: 4:00 PM</td>
<td>10/18/21: 5:30 PM</td>
<td>Yes</td>
</tr>
</tbody>
</table>
3.4 Model Validation

After creating the building model, the first step was to validate the model for unoccupied so that occupant-related influences like increased CO₂ transmission and increased room temperature can be determined. The goal behind validating the model for zero occupancy is to eliminate factors that could significantly affect data, prove that the model works for the unoccupied assumption, and use that model as a baseline to develop optimized solutions like considering ventilation strategies for occupancy.

The parameters that were found to have the greatest influence on the relative humidity and room air temperatures were: mechanical ventilation, natural ventilation, HVAC system outputs, outside air temperature, and air infiltration rate. Individual rooms (148, 219, 220, and 226) were used to validate the entire building by first developing a working model for those specific rooms and then applying those same conditions to the
rest of the building, since the building conditions and room conditions are essentially identical. While there were a few rooms in the science wing that had their own HVAC systems, the outputs of those HVAC systems are the same outputs as AHU-1 and AHU-2, which service most of the building. Figures 3.4 through 3.11 show the baseline models for each room, comparing the simulated air temperature and relative humidity results to the measured temperature and humidity. Note that the trends were correctly modeled and the average percent difference for temperature is less than 10%, and less than 15% for relative humidity, listed in Table 3.2. Note that the default year is 2002 for DesignBuilder, but the dates match the unoccupied room conditions data and use the weather data for June 2020.
Figure 3.4 Building 38 Room 148 Simulated vs Collected Room Temperature MATLAB Plot

Figure 3.5 Building 38 Room 148 Simulated vs Collected Relative Humidity MATLAB Plot
Figure 3.6 Building 38 Room 219 Simulated vs Collected Room Temperature MATLAB Plot

Figure 3.7 Building 38 Room 219 Simulated vs Collected Relative Humidity MATLAB Plot
Figure 3.8 Building 38 Room 220 Simulated vs Collected Room Temperature MATLAB Plot

Figure 3.9 Building 38 Room 220 Simulated vs Collected Relative Humidity MATLAB Plot
Figure 3.10 Building 38 Room 226 Simulated vs Collected Room Temperature MATLAB Plot

Figure 3.11 Building 38 Room 219 Simulated vs Collected Relative Humidity MATLAB Plot
Table 3.2 The percent differences between measured and simulated values are within 10% for room air temperature and within 20% for relative humidity.

<table>
<thead>
<tr>
<th>Room</th>
<th>Percent Difference (%) for Air Temperature and Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Air Temperature (°F)</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>38-148</td>
<td>5.08</td>
</tr>
<tr>
<td>38-219</td>
<td>1.73</td>
</tr>
<tr>
<td>38-220</td>
<td>1.77</td>
</tr>
<tr>
<td>38-226</td>
<td>6.35</td>
</tr>
</tbody>
</table>

The higher differences for relative humidity are likely from inaccurate building materials and room airtightness in the model but are still within adequate uncertainty. Thus, the model for relative humidity for unoccupancy could be improved. However, the model for room air temperatures results in maximum percent differences less than 10% and is considered accurate and valid for the purpose of this research. Simulation goals for relative humidity were to obtain a maximum percent difference no larger than 20%. As seen in Table 3.3, it was deemed that the percent differences between the simulated and collected data for room air temperature and relative humidity were acceptable for the full building model.

Table 3.3 The percent difference between measured and simulated values for room air temperature for June 2020 for the entirety of Building 38.

<table>
<thead>
<tr>
<th>Building</th>
<th>Percent Difference (%) for Air Temperature and Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Air Temperature (°F)</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>All of Building 38</td>
<td>5.97</td>
</tr>
</tbody>
</table>
Table 3.3 shows the data differences for the entirety of Building 38, rather than individual rooms. Although the room air temperature is within the acceptable range of 10%, the maximum data point that is yielded is 18.655%, which is high but still less than 20%. The higher percent difference could be due to averaging collected measurements from only four rooms—sensors were only placed in rooms 148, 219, 220 and 226. Because of this, the measured building air temperature that was used for the comparisons was the average temperature of all the measured room air temperatures. As for the relative humidity percent difference calculations for the whole of Building 38, the average and maximum percent differences are within the acceptable 20% range.

3.5 Post Processing: Excel and MATLAB

Excel was used to compile and sort the simulated data exported from DesignBuilder. Each time parameters were changed, new simulation results were obtained and exported from DesignBuilder to Excel. For the scope of this thesis, Excel served as an intermittent step that made importing the simulated data to MATLAB much easier. Excel was also used for plotting results.

For this thesis, MATLAB was used as a tool to assist with data analysis and visualization. The DesignBuilder data for this project was exported in 30-minute increments; whereas collected room data was reported in 5-minute increments. MATLAB scripts were used to import and compile the simulated DesignBuilder data from Excel, filter the data so that the timestamps of the simulated data match with the collected data, calculate the maximum percent difference between the two, and finally to plot the
simulated data against the collected data. Using MATLAB, the data trends influenced by changing parameters were much easier to visualize. By plotting the simulated data against the collected data, the goal was to undergo an iterative design process to understand the parameters that most greatly influenced the tuning of simulated data to resemble the collected data.

3.6 SIEMENS Building Data

Cal Poly facility operators use a SIEMENS BAS to monitor and adjust the campus HVAC systems. Some of the data that is measured is then transferred to a third-party software, called SkySpark. This password protected repository of operation and energy data was started in January 2020 for many of Cal Poly’s Buildings. Historical operation data was downloaded for the purpose of this research by permission from Dennis Elliot, Executive Director of Facility Operation at Cal Poly. The table below includes a list of data that was yielded from the SIEMENS GUI for AHU-1 and AHU-2.

<table>
<thead>
<tr>
<th>SIEMENS AHU #</th>
<th>Output Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHU-1, AHU-2</td>
<td>Mixed Air Temperature (°F)</td>
</tr>
<tr>
<td>AHU-1, AHU-2</td>
<td>Outside Air Damper Command (%)</td>
</tr>
<tr>
<td>AHU-1, AHU-2</td>
<td>Return Air Temperature (°F)</td>
</tr>
<tr>
<td>AHU-1, AHU-2</td>
<td>Supply Air Fan Status (ON/OFF)</td>
</tr>
</tbody>
</table>

Since rooms 148, 219, 220 and 226 are all in the math wing of Building 38, the AHU that is focused on is AHU-2, the sole AHU that operates in the math wing. The SIEMENS GUI is shown in Figure 3.12. Additional energy data that can be found in the SkySpark repository
for analysis of AHU-2 is listed below. Data is recorded every 5, 10, or 15 minutes and then can be averaged by hour, day, week, month, quarter, or year.

- Total Electric Meter – Demand and Usage
- Total HHW Meter – Usage
- Electric A/B – Demand and Usage
- HHW01/ HHW02 – Usage
- HHW BTU Meter, Raw

![AHU-2 Screenshot](image)

**Figure 3.12 Screenshot of SIEMENS GUI for AHU-2.**

### 3.7 Thermal Comfort Surveys

To further determine the current thermal comfort conditions as felt by real people, short surveys were given to occupants in Building 38 rooms 148, 219, and 220, (as well as 20-129, 20-203 and 33-286) to understand any differences between the expected PMV and PPD and the actual PMV and PPD of the students. Students were asked to complete an
anonymous 7-question survey at the end of their class. The survey aimed to determine whether the room conditions were acceptable and whether the student would want the room conditions changed. The survey included the following questions and options, as well as the PMV scale point distribution for each applicable option. (Note, the first two questions on the survey asked for research consent and to make sure all respondents were 18 or older as per Institutional Research Board (IRB) requirements.)

3. How did the temperature feel in the room?
   a. (-2) Cool
   b. (-1) Slightly cool
   c. (0) Neutral: neither cool nor warm
   d. (1) Slightly warm
   e. (2) Warm

4. How would you have preferred for it to feel?
   a. (-1) Cooler
   b. (0) No change
   c. (1) Warmer

5. How did you feel about the air circulation in the room?
   a. (-1) Need more
   b. (0) No opinion/no change
   c. (1) Need less

6. How humid did the room feel?
   a. (-2) Too dry
   b. (-1) Slightly dry
   c. (0) Just right
   d. (1) Slightly humid
   e. (2) Too humid

7. What clothing layers were you wearing?
   a. (0.5) Minimal [shorts, shirt]
   b. (0.74) Average [pants, shirt]
   c. (1) Heavy [pants, jacket/sweater/sweatshirt]

8. What activities have you done during class?
   a. Listen to lecture or speakers and/or take notes
   b. Take a quiz or exam
   c. Participate in class or small group discussions
   d. Work on assignments in class
   e. Gave a presentation/talk in front of the class
9. What was your stress level during class?
   a. (1) Very low
   b. (2) Low
   c. (3) Moderate
   d. (4) High
   e. (5) Very high

   Students filled out a fill-in-the-bubble-style survey sheet with their responses and the bubble sheets were read using a mobile app designed for the specific bubble sheet. The data from the surveys were compiled using a numerical ranking system to calculate the overall occupant PPD and PMV, and averages for questions 1-5 and 7. Table 3.5 lists the building, room, date, and time that surveys were given to students to receive feedback regarding the thermal comfort of their respective classes.

   As seen in Table 3.5, for Building 38, survey data was gathered for rooms 148, 219, and 220, which is directly related to the goals of this thesis report. The survey data collected from Buildings 2, 20, and 33, which are not directly related to the case studies of this thesis, the yielded data provides a more complete view of student comfort in classrooms. In addition, the extra survey data helps to generalize conclusions about overall student comfort, instead of based solely from the notoriously uncomfortable Building 38. There are room condition measurements (as denoted in Table 3.1) that respectively go along with collected survey data to help establish a stronger understanding of student comfort.
Table 3.5 Classrooms, dates, and times that surveys were collected regarding student thermal comfort during their classes.

<table>
<thead>
<tr>
<th>Room</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>38-148</td>
<td>10/28/2021</td>
<td>12:00 PM – 1:00 PM</td>
</tr>
<tr>
<td></td>
<td>10/29/2021</td>
<td>9:00 AM – 11:00 AM</td>
</tr>
<tr>
<td></td>
<td>11/1/2021</td>
<td>8:00 AM – 9:00 AM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11:00 AM – 12:00 PM</td>
</tr>
<tr>
<td>38-219</td>
<td>10/29/2021</td>
<td>2:00 PM – 3:00 PM</td>
</tr>
<tr>
<td></td>
<td>11/8/2021</td>
<td>7:00 AM – 8:00 AM</td>
</tr>
<tr>
<td>38-220</td>
<td>10/11/2021</td>
<td>9:00 AM – 10:00 AM</td>
</tr>
<tr>
<td></td>
<td>10/28/2021</td>
<td>10:00 AM – 12:00 PM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1:00 PM – 3:00 PM</td>
</tr>
<tr>
<td></td>
<td>10/29/2021</td>
<td>11:00 AM – 12:00 PM</td>
</tr>
<tr>
<td></td>
<td>11/1/2021</td>
<td>7:00 AM – 8:00 AM</td>
</tr>
<tr>
<td>02-203</td>
<td>10/4/2021</td>
<td>4:00 PM – 5:30 PM</td>
</tr>
<tr>
<td></td>
<td>10/6/2021</td>
<td>4:00 PM – 5:30 PM</td>
</tr>
<tr>
<td></td>
<td>10/18/2021</td>
<td>4:00 PM – 5:30 PM</td>
</tr>
<tr>
<td>20-129</td>
<td>10/20/2021</td>
<td>10:00 AM – 12:00 PM</td>
</tr>
<tr>
<td></td>
<td>10/22/2021</td>
<td>9:00 AM – 10:00 AM</td>
</tr>
<tr>
<td></td>
<td>11/10/2021</td>
<td>9:00 AM – 10:00 AM</td>
</tr>
<tr>
<td></td>
<td>11/12/2021</td>
<td>9:00 AM – 10:00 AM</td>
</tr>
<tr>
<td></td>
<td>11/17/2021</td>
<td>10:00 AM – 12:00 PM</td>
</tr>
<tr>
<td>33-286</td>
<td>10/15/2021</td>
<td>12:00 PM – 4:00 PM</td>
</tr>
<tr>
<td></td>
<td>11/19/2021</td>
<td>12:00 PM – 4:00 PM</td>
</tr>
</tbody>
</table>
Chapter 4

Results and Discussion

Chapter 4 discusses the results that were yielded from the different sections in the methods chapter. In Section 4.1, a detailed description and table are given to outline various parameters and their effects on thermal comfort during the modeling process. Section 4.2 discusses the results from different modeling scenarios including occupancy as well as ventilation approaches for the developed DesignBuilder models are compared to understand the effects of different strategies that would not be possible to experimentally explore with the actual building and its occupants. Next, the occupied February 2020 data when students were attending in-person classes, pre-COVID-19 lockdown, is compared to the occupied October 2021 data, when classes returned to being in-person and students returned to campus is shown in Section 4.3. Finally, in Section 4.4, the results from thermal comfort surveys are discussed, as well as the implications for building operation with respect to ventilation strategies.

4.1 Modeling – Effects of Different Parameters

From extensive simulation, it was determined that HVAC system outputs, number of occupants and their activity levels, outside air temperature, relative humidity, air infiltration rate, and mechanical/natural ventilation have the greatest impact on an occupant’s satisfaction with the room’s conditions. While outside air temperature and relative humidity are uncontrollable variables, it is found that having mechanical or
natural ventilation to filter indoor air with outdoor air is a very efficient way to improve IAQ.

This filtering of the air, also measured in air changes per hour, means that the pollutants that have accumulated in the room for any amount of time are removed and air returns to the space fresher and cleaner. As for thermal comfort, the HVAC system outputs, which are influenced by outdoor conditions, have a considerable effect on the room air temperature. Building 38’s SIEMENS HVAC systems service no AC in the main classrooms that are being modeled, making overheating a recurring issue, especially when it is warm outdoors and outside air is brought in for ventilation. The HVAC system is maintained at a heating setpoint temperature of 70°F and a cooling setpoint temperature of 76°F, which is set by CSU regulations for heating and cooling. [34] Setpoint temperatures are the temperature that the room is programmed to maintain based on air temperature. For example, if room temperature were to be measured to be 80°F and the cooling setpoint is 76°F, then the HVAC system will work to bring the room conditions to the setpoint temperature. The most ideal solution will be derived from optimizing both thermal comfort and IAQ—neither can be neglected. Table 4.1 shows the results for unoccupied rooms and changing different parameters in the building simulation. Given a set of parameters like the air infiltration rate, mechanical ventilation rate, mechanical ventilation area, presence of natural ventilation, setpoint temperatures, heat season coefficient of performance, and lighting, the percent differences for the respective rooms: 148, 219, 220, and 226 were found. The rows highlighted in green are the simulations that
yielded the lowest average percent difference while the row highlighted in red is the simulation that yielded the largest average percent difference.

There are two best case scenarios that were simulated. In both cases, air infiltration rate (air infil. in Table 4.1) set to 0.35 air changes per hour on a 7 AM to 10 PM schedule, natural ventilation (Nat. vent. in Table 4.1) turned off, heating setpoint and cooling setpoint (heat setpt, cool setpt in Table 4.1) at 70°F and 76°F respectively, and a heat season coefficient of performance (COP in Table 4.1) set to 0.85. The key difference between the two best conditions is that the mechanical ventilation in one case is set to option 2, in which the minimum fresh air required is calculated based on the number of people; whereas for the other case, the mechanical ventilation is set to option 3, in which the minimum fresh air required is calculated based on the area of the space. Air infiltration is defined as the movement of outside air into a building through cracks typically found in the building envelope and doors, which has an impact on the IEQ of a building. Natural ventilation is the utilization of natural forces like the wind to refresh the air in a room and provide fresh air. Unlike natural ventilation providing fresh air passively, mechanical ventilation actively forces and circulates fresh air into a building using ducts and fans. As mentioned above, for mechanical ventilation, option 3 calculates minimum fresh air required based on the area of the space. The mechanical ventilation area, given in \( \frac{ft^3}{min-ft^2} \), is the size of the space that is defined for calculating the minimum fresh air required. It can be noted in Table 4.1 that the mechanical ventilation area value is 0 up until option 3 is selected under the mechanical ventilation column, which is where the mechanical ventilation area begins to impact the results. The heat season COP is a
performance rating that tells us how effective a heat pump or air conditioner is at transferring heat versus the amount of electrical power it consumes. The movement from a low temperature area into a high temperature area requires work, and the COP says how effectively a heat pump or air conditioner performs this work by telling us the amount of power required by the machine to move a certain quantity of heat. [35] Additional conditions that influence the simulated data include the wall material, which can provide differing amounts of insulation, the window glazing, which can vary in types of glazing that affect insulation, natural shading to passively cool the building, and whether the building is occupied, which considerably affects the thermal comfort of the building.
Table 4.1 Building 38 DesignBuilder model simulation results. Variables were altered to understand how each of the variables affected percent difference for individual rooms and the whole building.

<table>
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4.2 Modeling – Occupancy and Ventilation Strategies

After validating the model for unoccupancy, the next step was to model occupancy and understand how closely the simulated data matches with the collected data for occupancy. The results for modeling occupancy in four classrooms are shown in Figures 4.1 through 4.4. Each figure shows the occupied model, as well as the measured room condition data and outside temperatures. Compared to the simulated and collected data for unoccupancy, the simulated data for occupancy yield considerably higher temperatures. When the outdoor temperatures are at positive or negative peaks, the occupied data appears to show that there is an offset and staggering as to when indoor temperatures reach their respective peaks—only after some time do indoor temperatures peak following outdoor temperatures peaking. Generally, the trend that can be seen with occupied temperatures is that they are much more sensitive to changes in outdoor temperature and fluctuate much more than unoccupied temperatures. After multiple hot days, when outdoor peak temperatures were above the high 80s, the occupancy model indicates that the building does not cool down for multiple days, even when outdoor temperatures drop down below 70°F. Even when outdoor temperatures exceed mid to high 80s, the occupied model indicates that indoor temperatures would be like the outdoor temperatures. However, when outdoor temperatures drop 15°F or more to below 70°F, the indoor temperatures only drop around 5°F rather than dropping much more to match the drop in outdoor temperature. This discrepancy in indoor temperatures remaining high despite lower outdoor temperatures is likely due to residual heat being
trapped inside the building. One solution that may rectify the issue could be to ventilate the building at night.

Figure 4.1 Comparison of occupied model against the measured unoccupied model based on outside weather for room 148.
Figure 4.2 Comparison of occupied model against the measured unoccupied model based on outside weather for room 219.

Figure 4.3 Comparison of occupied model against the measured unoccupied model based on outside weather for room 220.
Figures 4.5 through 4.8 provide visualization as to how two different ventilation strategies affect the room air temperature. Regular ventilation is scheduled as Monday through Friday, 7 AM to 10 PM; whereas the proposed 24/5 ventilation schedule would mean that the ventilation is functioning all throughout the day, Monday through Friday. Between the two schedules, the regular ventilation schedule consistently maintains higher temperatures than the 24/5 ventilation schedule does. It can be noted that the peak highs are similar; however, the regular ventilation schedule consistently maintains room temperatures at higher temperatures than the 24/5 schedule does. The peak lows vary much more in magnitude than the peak highs do because the 24/5 ventilation continues to operate even when outdoor temperatures reach daily lows during the...
middle of the night. Although the fall, summer, and spring data for room 219 yield similarly trending results between the two ventilation methods, the data yielded in winter for room 226 is very different. Note that for winter, when the temperature plateaus, the room's heating turning on. The peak highs for winter are comparable; however, there is an even greater magnitude difference in the peak lows for winter than there are for the other seasons. Like the trends seen in fall, summer, and spring, this is attributed by the fact that the 24/5 ventilation continues operating at night when outdoor temperatures typically reach daily lows. In San Luis Obispo, the winter weather is much colder than the other three seasons. So, the addition of significantly colder outdoor temperatures atop the 24/5 ventilation operating during cold winter nights results in the drastically lower room temperatures for the 24/5 ventilation schedule as opposed to the regular ventilation schedule, as seen in Figure 4.8, and is not needed as it is for the spring, summer, and fall.

![Figure 4.5 Comparison between the temperatures on a regular ventilation schedule vs a 24 hour, 5 days a week ventilation schedule during fall quarter for room 219.](image.png)
Figure 4.6 Comparison between the temperatures on a regular ventilation schedule vs a 24 hour, 5 days a week ventilation schedule during spring quarter for room 219.

Figure 4.7 Comparison between the temperatures on a regular ventilation schedule vs a 24 hour, 5 days a week ventilation schedule during summer quarter for room 219.
Figure 4.8 Comparison between the temperatures on a regular ventilation schedule vs a 24 hour, 5 days a week ventilation schedule during winter quarter for room 226.

Figure 4.9 shows the average high temperatures for each month for 5 different ventilation strategies. The 5 different ventilation strategies are regular ventilation, double regular ventilation, double 24/5 ventilation, regular ventilation 24/5, and regular ventilation 24/7. The minimum ventilation standards are described in Chapter 1.3 and are based on ASHRAE Standard 62.1 for the regular ventilation option, which operates from 7 AM – 10 PM. Double regular ventilation operates from 7 AM – 10 PM; however, the main distinction is that it operates at double the amount of the minimum ventilation values for regular ventilation. Double 24/5 is double the regular minimum ventilation values from ASHRAE Standard 62.1 from 2015, but instead operates for 24 hours a day, 5 days a week (Monday through Friday). Ventilation 24/5 functions at the regular minimum ventilation values but 24 hours a day, 5 days a week. The ventilation 24/7 strategy
operates at the regular minimum ventilation values but 24 hours a day, 7 days a week. All the different ventilation strategies resulted in reducing the peak temperature and based on the modeling, the double ventilation 24/5 is the best option for lowering the peak temperatures, especially during hotter months of the year.

Figure 4.9 Different ventilation strategies that show the average high temperatures per month.

Table 4.2 refers to Figure 4.9 and lists the changes seen in each of the ventilation strategies with respect to the regular ventilation strategy. Since the goal was to investigate which of the ventilation strategies best reduce the peak temperatures for different months, the main takeaway is to choose the ventilation strategy with the largest magnitude change. According to Table 4.2, the double 24/5 ventilation option produced the greatest average percent change and the greatest average temperature difference.

Table 4.2 shows the average temperature and average percent changes for the different ventilation strategies with respect to regular ventilation.

<table>
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<tr>
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<th>Double Reg Vent.</th>
<th>Double 24/5 Vent.</th>
<th>Vent 24/5</th>
<th>Vent 24/7</th>
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</thead>
<tbody>
<tr>
<td>Average Temp Difference</td>
<td>-0.81</td>
<td>-1.7</td>
<td>-0.95</td>
<td>-1.2</td>
</tr>
<tr>
<td>Average Percent Change</td>
<td>-1.1%</td>
<td>-2.3%</td>
<td>-1.3%</td>
<td>-1.6%</td>
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</table>
Figure 4.10 shows a comparison of the relationship between PPD vs PMV for regular ventilation and 24/5 ventilation strategies. In the 24/5 ventilation plot, the curve is shifted to the left—towards cooler PMV values—there are many more negative PMV datapoints, it is evident that the 24/5 ventilation schedule in Figure 4.10 achieves much colder temperatures according to the PMV axis. Both plots appear to span to very similar maximum positive PMV values, while the PPD at those values are comparable. On the other hand, the maximum magnitude of PMV in the negative direction for the 24/5 schedule is much greater than the maximum magnitude of PMV in the negative direction for the regular schedule, which contributes to a higher PPD for the 24/5 maximum. It can be gathered that rather than having a ventilation schedule that achieves colder overall temperatures like the 24/5 schedule, may be better for occupants, especially since student survey data (from [24] and discussed in Section 4.4) indicates that students would prefer cooler temperatures.

![Figure 4.10 Comparison between the PPD on a regular ventilation schedule vs a 24 hour, 5 days a week ventilation schedule.](image-url)
Table 4.3 shows a count comparison of the number of hours the model predicts Building 38 room 148 to be cold, neutral, or hot between the 24/5 ventilation and regular ventilation strategies. The comparison is for fall quarter, which is from September to December, during the hours of 8 AM – 9 PM, and explains the PMV shift in Figure 4.10. The 24/5 ventilation counts are based on PMV scores: less than -0.5 for cold and greater than 0.5 for hot. According to Table 4.3, the 24/5 ventilation data shows that there are 51 recorded hours that can be constituted as hot, while the regular ventilation shows there are 110 hot hours, which means that with the 24/5 ventilation, the number of hot hours is halved, which is illustrated in Figure 4.10. This major decrease in the number of recorded hot hours ultimately influences the model predictions for the number of neutral and cold hours that should be expected when implementing a 24/5 ventilation schedule instead of the regular ventilation schedule. The number of neutral hours is decreased from 689 hours to 531 hours and the number of cold hours is increased from 489 hours to 706 hours. Additionally, the model predicts that the percentage of neutral student should decrease from 53% to 41% while the percentage of cold students should increase from 38% to 55%, indicating that the room feels much cooler with 24/5 ventilation.
Table 4.3 24/5 ventilation vs regular ventilation model comparison for 38-148, count and percent of the number of hours classified as cold (PMV<-0.5), neutral or hot (PMV > 0.5)

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<tr>
<td>Total</td>
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<td>1288</td>
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<td>Cold</td>
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<td>489</td>
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<tr>
<td>Neutral</td>
<td>531</td>
<td>689</td>
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<tr>
<td>Hot</td>
<td>51</td>
<td>110</td>
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Tables 4.4 and 4.5 both show model data comparing double ventilation 24/5 to regular ventilation for Building 38 room 220. By evaluating the data in Table 4.4 for PMV, based on the counts and percentage of counts for hot, neutral, and cold, it can be concluded that with the double ventilation 24/5, the rooms become considerably cooler during the afternoon, which is from 12 PM – 4 PM. During the afternoon, the model predicts that number of hot hours drop from 194 to 97 when double ventilation 24/5 is in operation and the predicted number of neutral hours drops from 833 hours to 524 hours; however, the model predicts that the number of cold hour instances increases from 798 hours to 1,204 hours. This change is most notably seen with the percentage change between regular ventilation and double ventilation 24/5. The percentage of counts that are predicted to be cold increases from 44% to 66%, while the percentage of counts for neutrality decreases from 46% to 29% and for hot decreases from 11% to 5%. Table 4.5 shows the model results specifically during afternoons in the month of September. The model predicts that students should feel colder with the double ventilation 24/5 in effect. Of the 150 hours, the regular ventilation strategy predicts that
there will be 46 hot hours, 56 neutral hours, and 48 cold hours, while the double ventilation 24/5 model predicts that there will be 28 hot hours, 48 neutral hours, and 74 cold hours. The model indicates that although the number of hot and neutral students should decrease for the month of September, the number of cold students should increase.

Table 4.4 Double ventilation 24/5 vs regular ventilation model comparison for 38-220

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<td>Cold</td>
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<td>Neutral</td>
<td>524</td>
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<td>Hot</td>
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<td>194</td>
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% Cold: 66% Neutral: 29% Hot: 5%

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<td>Cold</td>
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<td>Hot</td>
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% Cold: 42% Neutral: 39% Hot: 19%

Table 4.5 September Double ventilation 24/5 vs regular ventilation model comparison for 38-220 during afternoons

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<td>Hot</td>
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% Cold: 42% Neutral: 39% Hot: 19%

4.3 Operating Conditions – Pre- and During COVID-19

In this section, the focus is comparing the occupied February 2020 data, which is pre-COVID-19 and when students were still on campus, and the occupied October 2021 data,
which is when students fully returned to campus during COVID-19. The data that is compared between the two months is for AHU-2 (Figure 3.12), which was downloaded from the SkySpark repository. Room conditions that were measured using AHU-2 include the return air temperature, mixed air temperature, outside air damper command, and the supply air fan status. Although Building 38 has multiple AHUs operating within it, the key AHU for this thesis is AHU-2 because rooms 148, 219, 220, and 226 are all located in the math wing of Building 38, which is covered by AHU-2.

The return air temperature is representative of the room temperatures during the day as shown in Figure 4.11 for October 2021. Note that unlike rooms 219 and 220, which had data taken from November 1st, data for room 148 did not start being taken until November 21st. During the night, when the system is off, the return air temperature drops to be representative of the outdoor temperature, which makes sense because the air is quiescent in a duct that is one the roof and more exposed to outdoor conditions that the classrooms indoors. The mixed air temperature is the temperature after mixing the return air and the outside air, before any heating by the AHU, and is representative of the ratio of outside to return air that is circulated back into the building. We know, based on the SIEMENS building data, that heating was on in both February 2020 and October 2021. According to correspondence with facilities, heat is typically on in buildings from October through April. [36] Buildings at Cal Poly are heated using a central hot-water piping network that is supplied and modulated by the Cal Poly Central Plant. At building AHUs, supply air is passed through a hot-water to air heat exchanger (example shown in Figure 3.12 of the AHU-2 SIEMENS GUI). The hot water usage for February 2020, was 140 kBTU
and for October 2021, the hot water usage was 83 kBTU. The difference between the two months represents the difference in heating needs based on the outdoor temperatures.

![Figure 4.11 Comparison between the return air temperature, outside temperature and average room temperature for rooms 148, 219, and 220 in October 2021.](image)

Figure 4.11 Comparison between the return air temperature, outside temperature and average room temperature for rooms 148, 219, and 220 in October 2021.

The damper command on the AHU designates how much outside air is mixed with the recirculated building air and provides a cleaner space for occupants and improve air quality. Recall that according to ASHRAE Standard 62.1 there is a minimum outside air ventilation requirement. Figure 4.12 and Table 4.6 compare the damper command for AHU-2 in February 2020 and October 2021. The damper command is turned on during the weekdays from 8 AM to 10 PM and is turned off at night and during the weekend, as seen from the damper command percentage. Note the two different horizontal axes, one for October and one for February in Figure 4.12.
Figure 4.12 is a comparison of the percent the damper was opened for Building 38 in February 2020 vs October 2021. It was expected and confirmed by the data that the damper would be open more in October 2021 than February 2020 to allow more outside airflow through ducts. The idea behind this was to create an acceptable indoor environment since students would return to campus at this time and COVID is still a major public health concern.

Table 4.6 summarizes the differences in damper percent opening between February 2020 and October 2021.

<table>
<thead>
<tr>
<th>AHU-2 Damper Command Percent Open</th>
<th>February 2020 Count</th>
<th>October 2021 Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 % (closed and fan off)</td>
<td>354</td>
<td>534</td>
</tr>
<tr>
<td>1 – 19.9%</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>20 – 29.9%</td>
<td>185</td>
<td>0</td>
</tr>
<tr>
<td>30 – 39.9%</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td>40 – 49.9%</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>50 – 59.9%</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>60 – 69.9%</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>70 – 79.9%</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>80 – 89.9%</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>90 – 100%</td>
<td>30</td>
<td>210</td>
</tr>
</tbody>
</table>

The damper command for AHU-2 is nearly 100% open for the entirety of October 2021, when on; whereas in February 2020, the damper command opening percentage varies between 29% and 100%, and most of the time is at 29% when open. The damper
command open 100% in October 2021 means that the AHU is using 100% outside air for
circulation throughout the building and makes sense for additional ventilation needs
because of COVID-19. Since February 2020 represents pre-COVID-19 time, it can be
assumed that 29% damper opening is the requirement to maintain the required minimum
ventilation for Building 38. For February 2020, there is no explanation or pattern to
describe why the damper command is open greater than 29%. Table 4.6 illustrates the
significant differences in damper percentage opening between February 2020 and
October 2021 by listing how many datapoints (hours) were within each of the percent
opening ranges. The distribution of damper opening from February 2020 changes from
having a wide spectrum of operating opening percentages to the damper being either
open or not, which is evident in October 2021. In October 2021, which is when students
returned to campus, the damper was fully open when students were in classrooms to
circulate fresh air into the building and help promote a safer learning environment.

Figure 4.13 is a screenshot from the SIEMENS SkySpark data for Building 38 for
AHU-2 in February 2020. The four sub-plots show the following information for February
2020: outdoor air temperature (top), mixed air temp & return air temp for AHU-2 (second
subplot), outside air damper opening for AHU-2 (third subplot), and the supply air fan
status for AHU-2 (bottom). The average high outside temperature was 64.9°F and the
peak maximum is 74°F. The average outside low temperature was 46°F and the lowest
low was 34°F. For February 2020, the average indoor high was calculated to be 70°F and
the average indoor low was calculated to be 52.9°F. It can be assumed that the minimum
outside temperatures occur during the middle of the night, which is when daily lows are
frequent and is when classrooms are not occupied. In the second subplot—mixed air temperature and return air temperature—a pattern can be observed on the weekdays when the return air temperature pseudo-plateaus during the day and drops at night—reaches a minimum temperature—before increasing again when the heat turns on and pseudo-plateaus again. The heating setpoint temperature for AHU-2 is 70°F—the value at which the return air temperature consistently plateaus. On weekends however, since AHU-2 is turned off, the return air temperature plot does not follow the previously mentioned pattern, but instead appears to closely match the mixed air temperature, which makes sense. Note that for the first 3 weeks, heating and controls helped maintain the indoor room temperature at 70°F, but in fourth week, the indoor temperatures were higher than the setpoint temperature. This may be caused by a higher outdoor temperature during that week in comparison to the previous 3 weeks. The bottom subplot in the figure below shows whether the supply fan is turned on or turned off. Just like the return air temperature and damper command plots, the supply fan is turned on during the weekdays and turned off during the weekends. The third subplot in Figure 4.13 shows the damper opening range between 29% and 100% during weekdays when the fan is on; however, there is no obvious reason that the damper is open greater than 29% for February based on outdoor and indoor temperatures. When the damper is turned off over the weekend, the damper opening falls to 0%. All four subplots together give us a picture of the AHU operation in February 2020.
Figure 4.13 SIEMENS SkySparks data for Building 38’s AHU-2 in February 2020.

Figure 4.14 shows a screen shot from the SIEMENS SkySpark data for Building AHU-2 from October 2021. The plots below show the following information for October 2021: outdoor air temperature (top subplot), mixed air temp & return air temp for AHU-2 (middle subplot), and the supply air fan status for AHU-2 (bottom subplot). For October 2021, the outside damper is either 0% when turned off during the weekend or is 100% open during the weekday, and thus is not shown in Figure 4.14. The peak outside temperature is 89°F and the lowest temperature is 46°F. Based on data exported from SkySparks, the average
indoor high was calculated to be 73°F and the average indoor low was calculated to be 57.6°F, while the average outdoor high was 74.4°F and the outdoor average low was 51.9°F. It can be assumed that the minimum outside temperatures occur during the middle of the night, which is when daily lows are frequent and is when classrooms are not occupied. In the second subplot—mixed air temperature and return air temperature—a similar pattern to February 2020 can be seen during the weekdays where the return air temperature plot pseudo-plateaus, drops, reaches a minimum, rises, and pseudo-plateaus again. The heating setpoint temperature for AHU-2 is 70°F, which is the value the return air temperature would ideally to plateau at, similar to February 2020; however, given the high outside temperatures and that the damper is 100% open in October—the indoor temperatures are affected and are higher than 70°F. Note that on the third week, the heating system appears to maintain temperatures very close to 70°F during the cooler week. Additionally, it can be noted that there is less heating in October compared to February because of October’s warmer outside temperature, and the fact that the damper is 100% open during occupancy. The effect of the outdoor temperature on the indoor temperature is clear since there is no cooling in AHU-2 and the second subplot provides excellent visualization as to how maintaining 70°F is tougher in October than February, especially when the 100% outside air is used. On weekends however, since AHU-2 is turned off, the return air temperature plot does not follow the previously mentioned pattern, but instead appears to closely resemble the mixed air temperature plot. The last subplot in Figure 4.14 shows when the supply fan is turned on or turned off. Just like the return air temperature and damper command plots, the supply fan is turned
on during the weekdays and off during the weekend. Note that the tabulated data for Figure 4.14 indicates that the fans were only operational until 5 PM instead of the standard 10 PM. Implications of the fan turning off early will be shown and discussed below.

*Figure 4.14 SIEMENS SkySparks data for Building 38’s AHU-2 in October 2021.*
The difference between the two temperatures (mixed air temperature minus the return air temperature) is representative of the amount of heat added to the air, either via heating before entering the building or from the people (as well as lights and electronic equipment) in the building. The air temperature difference is plotted in Figure 4.15 for each time frame. Positive values indicate that heat has been added, while negative values denote heat loss. A count of positive, negative, and neutral values is tabulated in Table 4.7. The counts are separated by typical occupied times—hours 8 AM to 9 PM denoted in military time—and unoccupied times—10 PM to 7 AM. The higher return temperatures (positive differences) occur more often during occupied times, which makes sense because that is when people are in the building, heating is on, and lights/electronics are in use.

Figure 4.15 shows the difference in return air temperature and mixed air temperature. A positive value indicates a higher return air temperature with respect to mixed air temperature and a negative value indicates a lower return air temperature with respect to mixed air temperature. It can be noted that for February 2020 and October 2021, the data spread appears to be relatively similar.
Table 4.7 references Figure 4.15. It shows the distribution of the positive, negative, and neutral differences in temperature during occupied and unoccupied times for February 2020 vs October 2021.

<table>
<thead>
<tr>
<th></th>
<th>Feb (+)</th>
<th>Feb (-)</th>
<th>Feb (0)</th>
<th>Oct (+)</th>
<th>Oct (-)</th>
<th>Oct (0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08-21 count</td>
<td>299</td>
<td>104</td>
<td>3</td>
<td>223</td>
<td>203</td>
<td>8</td>
</tr>
<tr>
<td>22-07 count</td>
<td>40</td>
<td>218</td>
<td>4</td>
<td>24</td>
<td>285</td>
<td>1</td>
</tr>
<tr>
<td>Total column count</td>
<td>339</td>
<td>322</td>
<td>7</td>
<td>247</td>
<td>488</td>
<td>9</td>
</tr>
<tr>
<td>Total Count for Feb: 568</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Count for Oct: 744</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Upon inspection of Figures 4.13 and 4.14, neutral values (i.e., no difference between the two temperatures) are most likely to occur on weekends when the system is off, which makes since there is no forced air movement through the system and temperatures equalize in the AHU. As seen in the table, the number of times that are positive or negative Delta T for October 2021 during occupied times is much more evenly spread between the positive and negative than it is in February 2020. There is more heating in February, and colder outdoor temperatures, though the outside air contribution is less, typically at 29% open damper control. Table 4.8 summarizes the high and low temperatures for February 2020 and October 2021. The data between the two months is comparable and has similar patterns to what we would expect for outdoor temperatures on the CA central coast. As seen in Figures 1.2 through 1.9, the CBE Thermal Comfort tool shows how there is a wide comfort zone that is acceptable for students. There are many possible scenarios that yield room conditions that students find comfortable. Based on proper clothing insulation, there are a variety of acceptable conditions that can be noted. Although Table 4.8 does not include relative humidity, it can be hypothesized that except for the hottest of temperatures in October, the room
temperatures should be fine during class times. According to the CBE Thermal Comfort tool, since there are a variety of acceptable conditions that are defined by the comfort zone, these temperatures should be acceptable.

Table 4.8 Summary of highs and low temperatures for February 2020 and October 2021.

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Average Highs, Lows for Month (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indoor High</td>
</tr>
<tr>
<td>February 2020</td>
<td>70.0</td>
</tr>
<tr>
<td>October 2021</td>
<td>73.0</td>
</tr>
<tr>
<td></td>
<td>Highs, Lows Range (°F)</td>
</tr>
<tr>
<td>February 2020</td>
<td>61.9-75.68</td>
</tr>
<tr>
<td>October 2021</td>
<td>64.5-81.25</td>
</tr>
</tbody>
</table>

As previously discussed, the air quality in the classrooms is critical. Figure 4.16 shows the measured CO2 concentration in Building 38, Rooms 148, 219, and 220 for Fall 2021. Unfortunately, we do not have any pre-COVID CO2 measurement data. As seen in Figure 4.16, at 17:00 (5 PM), the CO2 concentration dramatically increases for 3 hours in rooms 220 and 219. One reason for this spike could be caused by fans shutting off at 5 PM, as indicated by the SIEMENS building data, even though the rooms are still occupied during this time. Given that the maximum allowed CO2 concentration for a healthy room is rated at 1,000 ppm, the spike in CO2 concentration between 5 PM and 8 PM is problematic. The last class in room 148 ends at 3 PM; whereas the last classes in rooms 219 and 220 end at 8 PM. [37] Without having the air circulate properly, the CO2 concentration accumulates the most between 5 PM and 7 PM and then steeply decreases once there are no longer any classes held in the rooms for the day. We do not know why
the fans were turned off at 5 PM instead of 10 PM for Fall 2021 compared to pre-COVID operation in February 2020.

Figure 4.16 shows the CO₂ concentration in rooms 148, 219, and 220 with respect to the time (hour) of day. It is evident that there is a steep increase in the CO₂ concentration between 5 PM and 7 PM—with many datapoints in that timeframe exceeding the acceptable CO₂ limit of 1,000 ppm for a safe indoor environment.

4.4 Student’s Thermal Comfort Perceptions and Opinions

The surveys described in Chapter 3 were compiled to understand student thermal comfort preferences. Additionally, the surveys were used to compare the predicted thermal comfort from the modeling process to how students reported they felt. By understanding the thermal comfort preferences of occupants yielded from the results, the model could be further developed to test new ventilation strategies that would reflect occupant preferences, for example, maintaining rooms at cooler temperatures. The
survey efforts produced 744 responses—results summarized in Tables 4.9 and 4.10—which amounted to a variety of conclusions. The thermal sensation was averaged (TC ave PMV in the table), and well as the average change in thermal sensation, air circulation, humidity and stress are listed in Table 4.9 by survey date, room, and time. The percent of students not at neutral (% S not neutral TC) was based on question 4, which asked if students were happy, or wanted it to be cooler or warmer. The “change ave” indicates if whether students want the room to be cooler (negative values) or warmer (positive values). PMV values that were positive indicated a warm room, while PMV values that were negative indicated a cooler room, and the greater the magnitude of the PMV—the greater the intensity of the warmness or coolness. Classroom PMV values that were closer to 0 are indicative that the classroom conditions were just slightly too warm or cool, depending on the whether the value was positive or negative. Table 4.10 lists the total count and percent of students wearing different types of clothes and what type of activities were occurring during class. Although 31% of students were found to be dressed lightly, 48% dressed average, and 21% dressed heavily, students tend to prefer for their respective rooms to be cooler than they were. Students from 19 of the 28 classes reported that they felt too warm in their respective classes. Additionally, all 28 classes, on average, responded that the room needed more air circulation to be more comfortable and acceptable by students. According to Table 4.10, the most common activities that students reported in their classes were taking notes during lecture, which totaled to 93% of students, and taking a quiz or test, which 43% of students reported. Besides the most common activities, 31% of students participated in group discussions while 22% answered
that they worked on assignments in class. Of the 28 classes that data was taken for, only
3 classes reported that they preferred for the room to be warmer than it was—the 25
other instances indicated that they preferred the rooms to be cooler.

Table 4.9 Summary of the collected class average survey data that show student thermal
comfort. The column headings indicate which question on the survey the results are based
on.

<table>
<thead>
<tr>
<th>Room</th>
<th>Date</th>
<th>Time</th>
<th>Number Survey Answers</th>
<th>TC ave (#3) PMV</th>
<th>% S not Neutral TC (#4)</th>
<th>change Ave (#4)</th>
<th>air circ (#5)</th>
<th>humidity (#6)</th>
<th>ave stress (#9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38-220</td>
<td>10.28</td>
<td>2-3pm</td>
<td>22</td>
<td>1.18</td>
<td>86%</td>
<td>-0.9</td>
<td>-0.9</td>
<td>0.5</td>
<td>3.4</td>
</tr>
<tr>
<td>38-220</td>
<td>10.28</td>
<td>10-11am</td>
<td>26</td>
<td>0.17</td>
<td>54%</td>
<td>-0.45</td>
<td>-0.62</td>
<td>-0.03</td>
<td>2.3</td>
</tr>
<tr>
<td>38-220</td>
<td>10.28</td>
<td>1-2pm</td>
<td>33</td>
<td>1.36</td>
<td>82%</td>
<td>-0.82</td>
<td>-0.79</td>
<td>0.70</td>
<td>3.1</td>
</tr>
<tr>
<td>38-220</td>
<td>10.28</td>
<td>11-12pm</td>
<td>19</td>
<td>0.38</td>
<td>53%</td>
<td>-0.48</td>
<td>-0.76</td>
<td>0.05</td>
<td>2.3</td>
</tr>
<tr>
<td>38-220</td>
<td>10.29</td>
<td>11-12pm</td>
<td>25</td>
<td>0.68</td>
<td>80%</td>
<td>-0.8</td>
<td>-0.6</td>
<td>0.28</td>
<td>2.3</td>
</tr>
<tr>
<td>38-220</td>
<td>11.1</td>
<td>7-8am</td>
<td>23</td>
<td>-0.30</td>
<td>39%</td>
<td>0.04</td>
<td>-0.39</td>
<td>-0.04</td>
<td>2.8</td>
</tr>
<tr>
<td>38-220</td>
<td>10.11</td>
<td>9-10am</td>
<td>24</td>
<td>-0.29</td>
<td>50%</td>
<td>-0.08</td>
<td>-0.42</td>
<td>-0.50</td>
<td>2.8</td>
</tr>
<tr>
<td>38-148</td>
<td>10.28</td>
<td>12-1pm</td>
<td>32</td>
<td>0.78</td>
<td>88%</td>
<td>-0.88</td>
<td>-0.84</td>
<td>-0.06</td>
<td>2.4</td>
</tr>
<tr>
<td>38-148</td>
<td>10.29</td>
<td>9-10am</td>
<td>20</td>
<td>0.10</td>
<td>60%</td>
<td>-0.3</td>
<td>-0.15</td>
<td>-0.1</td>
<td>2.1</td>
</tr>
<tr>
<td>38-148</td>
<td>10.29</td>
<td>10-11am</td>
<td>32</td>
<td>0.28</td>
<td>53%</td>
<td>-0.47</td>
<td>-0.66</td>
<td>-0.03</td>
<td>2.7</td>
</tr>
<tr>
<td>38-148</td>
<td>11.1</td>
<td>11-12pm</td>
<td>27</td>
<td>0.52</td>
<td>52%</td>
<td>-0.48</td>
<td>-0.41</td>
<td>0.10</td>
<td>2.25</td>
</tr>
<tr>
<td>38-148</td>
<td>11.1</td>
<td>8-9am</td>
<td>19</td>
<td>-0.89</td>
<td>32%</td>
<td>0.11</td>
<td>-0.37</td>
<td>-0.37</td>
<td>1.78</td>
</tr>
<tr>
<td>38-219</td>
<td>10.29</td>
<td>2-3pm</td>
<td>24</td>
<td>-1.00</td>
<td>54%</td>
<td>0.54</td>
<td>-0.04</td>
<td>-0.38</td>
<td>2.22</td>
</tr>
<tr>
<td>38-219</td>
<td>11.8</td>
<td>7-8am</td>
<td>16</td>
<td>1.31</td>
<td>81%</td>
<td>-0.81</td>
<td>-0.88</td>
<td>0.56</td>
<td>3.06</td>
</tr>
<tr>
<td>02-203</td>
<td>10.4</td>
<td>4-5:30pm</td>
<td>44</td>
<td>0.77</td>
<td>75%</td>
<td>-0.70</td>
<td>-0.59</td>
<td>0.30</td>
<td>2.47</td>
</tr>
<tr>
<td>02-203</td>
<td>10.6</td>
<td>4-5:30pm</td>
<td>33</td>
<td>-0.06</td>
<td>55%</td>
<td>-0.48</td>
<td>-0.21</td>
<td>0.24</td>
<td>2.33</td>
</tr>
<tr>
<td>02-203</td>
<td>10.18</td>
<td>4-5:30pm</td>
<td>27</td>
<td>-0.26</td>
<td>30%</td>
<td>-0.22</td>
<td>-0.19</td>
<td>-0.07</td>
<td>2.26</td>
</tr>
<tr>
<td>20-129</td>
<td>10.22</td>
<td>9-10am</td>
<td>23</td>
<td>-0.09</td>
<td>61%</td>
<td>-0.17</td>
<td>-0.35</td>
<td>0.17</td>
<td>2.30</td>
</tr>
<tr>
<td>20-129</td>
<td>11.10</td>
<td>9-10am</td>
<td>23</td>
<td>-0.22</td>
<td>39%</td>
<td>-0.13</td>
<td>-0.30</td>
<td>0.30</td>
<td>2.22</td>
</tr>
<tr>
<td>20-129</td>
<td>11.12</td>
<td>9-10am</td>
<td>22</td>
<td>-0.09</td>
<td>45%</td>
<td>-0.18</td>
<td>-0.18</td>
<td>-0.05</td>
<td>2.05</td>
</tr>
<tr>
<td>20-129</td>
<td>11.17</td>
<td>10-11am</td>
<td>23</td>
<td>0.30</td>
<td>52%</td>
<td>-0.52</td>
<td>-0.65</td>
<td>0.30</td>
<td>2.48</td>
</tr>
<tr>
<td>20-129</td>
<td>11.17</td>
<td>11-12pm</td>
<td>18</td>
<td>1.06</td>
<td>83%</td>
<td>-0.83</td>
<td>-0.94</td>
<td>0.44</td>
<td>3.11</td>
</tr>
<tr>
<td>20-129</td>
<td>10.20</td>
<td>10-11am</td>
<td>30</td>
<td>0.27</td>
<td>63%</td>
<td>-0.63</td>
<td>-0.77</td>
<td>0.23</td>
<td>2.93</td>
</tr>
<tr>
<td>20-129</td>
<td>10.20</td>
<td>11-12pm</td>
<td>34</td>
<td>0.71</td>
<td>59%</td>
<td>-0.47</td>
<td>-0.68</td>
<td>0.35</td>
<td>3.03</td>
</tr>
<tr>
<td>33-286</td>
<td>10.15</td>
<td>12-2pm</td>
<td>47</td>
<td>0.77</td>
<td>68%</td>
<td>-0.75</td>
<td>-0.60</td>
<td>0.35</td>
<td>1.92</td>
</tr>
<tr>
<td>33-286</td>
<td>10.15</td>
<td>2-4pm</td>
<td>48</td>
<td>1.17</td>
<td>79%</td>
<td>-0.79</td>
<td>-0.63</td>
<td>-0.06</td>
<td>1.90</td>
</tr>
<tr>
<td>33-286</td>
<td>11.19</td>
<td>12-2pm</td>
<td>22</td>
<td>0.45</td>
<td>59%</td>
<td>-0.59</td>
<td>-0.68</td>
<td>0.00</td>
<td>1.64</td>
</tr>
<tr>
<td>33-286</td>
<td>11.19</td>
<td>2-4pm</td>
<td>8</td>
<td>0.25</td>
<td>63%</td>
<td>-0.625</td>
<td>-0.5</td>
<td>0.125</td>
<td>1.625</td>
</tr>
</tbody>
</table>
Table 4.10 shows student clothing trends and the most common activities that students completed during their respective classes.

<table>
<thead>
<tr>
<th></th>
<th>Cloth light (0.5 clo)</th>
<th>Cloth avg (0.74 clo)</th>
<th>Cloth heavy (1.0 clo)</th>
<th>Activity: Listen to lecture/take notes</th>
<th>Activity: Take quiz/exam</th>
<th>Activity: In-class group discussion</th>
<th>Activity: In-class work</th>
<th>Activity: Presentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>234</td>
<td>354</td>
<td>158</td>
<td>695</td>
<td>320</td>
<td>232</td>
<td>161</td>
<td>7</td>
</tr>
<tr>
<td>Percent</td>
<td>31%</td>
<td>48%</td>
<td>21%</td>
<td>93%</td>
<td>43%</td>
<td>31%</td>
<td>22%</td>
<td>1%</td>
</tr>
</tbody>
</table>

It was found that students tend to generally have higher average stress levels when activities done in class include taking a quiz or an exam, as opposed to other common activities like taking notes during lecture. It was reported by the professor that data taken in 20-129 for the 10 AM to 11 AM and 11 AM to 12 PM classes were collected after students took a quiz, which validates the higher average stress levels. The reported average stress levels that students felt during these classes were 2.48, 3.11, 2.93, and 3.03. Respective to the rest of the data taken, the stress levels during these classes were notably higher than for most of the other classes. Additionally, it was found that average stress levels for lecture classes was about 2.5 while average stress levels for freshman seminar was found to be 1.7. This makes sense since first-year seminar does not include quizzes or exams. The first-year seminars are lower stress class meetings since the purpose of the seminar is to prepare students for success in college and a high stress situation would not accommodate this.

Figure 4.17 is a plot of each of the classroom averages for the stress levels with respect to measured room temperatures that were recorded from the surveys. For each class, the stress that each of the students felt was averaged to understand whether the indoor temperature played a role in affecting student stress levels. According to Figure
4.17, it can be concluded that there is no relationship between student stress and room temperature.

![Graph showing relationship between average stress and room temperature.](image)

*Figure 4.17 shows the relationship between average stress collected from the survey and the average measured room temperature.*

Figure 4.18 shows how clothing insulation of occupants change with respect to the outdoor temperature. Although the data appears to be mostly a scatterplot for all three clothing insulations, there seems to be a linear relationship trendline that can be drawn for the data. The data shows how the percentage of students wearing light clothing starts low but increases as the outdoor temperature increases. On the other hand, the percentage of students wearing medium clothing and heavy clothing starts high and decreases as the outdoor temperature increases. Figure 4.19 shows how the outdoor temperature changes during the day. This change in outdoor temperature influences the indoor temperature of the building, which directly affects student thermal comfort. As expected, the afternoon is warmer than early morning or late night. The curve fit seen in
both orange and grey are the trendlines for the indoor and outdoor temperatures respectively. As outdoor temperature increases with respect to time, there’s a general square root function trend in indoor temperature increasing along with the survey PMV. The outdoor temperature can also influence what students wear.

Figure 4.18 shows the relationship between the percent of students in class wearing different clothing insulations with respect to the outdoor temperature.

Figure 4.19 shows the relationship between outdoor temperature changes throughout the day and how that affects indoor temperature and ultimately the survey PMV.
Figures 4.20 and 4.21 shows the relationships between the percentage of uncomfortable students (percent students not neutral) to outdoor temperature and survey PMV respectively. Figure 4.20 provides a visualization as to how the percent of students not neutral with thermal comfort conditions is influenced by the outdoor temperature. Based on the data, it can be hypothesized that higher outdoor temperatures lead to a higher percentage of students not neutral with indoor conditions. As seen in Figure 4.21, classrooms that reported positive (warmer classrooms) average PMV generally tend to have higher percentages of students who are unaccepting of the room’s thermal comfort, as opposed to classrooms that reported negative (cooler classrooms) average PMV. Of the total 27 measurements, 6 of the total 9 rooms with negative PMVs reported student unacceptance of 50% or less while all 18 of the rooms with positive PMVs reported student unacceptance of higher than 50%. There is a positive linear relationship between classroom PMV and the percent of students not neutral, which is shown in Figure 4.21.
Figure 4.21 shows a positive relationship between the average thermal comfort of the classroom, represented in PMV, and the percent of students who do not feel neutral with the room's thermal comfort. Generally, the higher percent of students dissatisfied with the thermal comfort of the room comes from classrooms with positive PMVs, indicating a warm environment.

Figure 4.22 below illustrates the measured conditions in the classes, specifically the average thermal comfort (PMV) with respect to average measured room temperature. Room 148 shows a positive relationship in the sense that lower average room temperatures result in lower PMV values whereas higher average room temperatures result in higher average PMV values. Like room 148, room 220 also yields a positive correlation between average PMV and average measured room temperature. It is found that for average room temperatures less than 70°F, the average PMV is negative, while for temperatures greater than 70°F, the average PMV is positive.
Figure 4.22 shows the relationship between the average measured PMV and the average measured room temperature. For rooms 148 and 220, a positive correlation between average measured PMV and average measured room temperature can be seen.

Figure 4.23 shows a negative linear correlation between the average PMV and the PMV change wanted. This means that generally, when the PMV is positive, which indicates that the occupants felt the room was too warm, the occupants preferred for the room to feel cooler. Of the 28 total datapoints, 25 classes on average preferred for the room to be cooler while only 3 classes on average preferred for the room to be warmer. Of the 9 negative average PMV values, which indicate a cooler room, occupants for 6 of the classrooms preferred for the room to be even cooler than it was measured to be. Like Figure 4.23, Figure 4.24 shows a similar relationship and negative correlation between the measured average indoor temperature and the average preferred change in temperature. Although Figure 4.23 describes the relationship between PMV and preferred PMV, Figure 4.24 provides the same conclusion—an overwhelming number of students prefer to feel cooler, given higher temperatures. The cutoff where students preferred a positive change in temperature value is at roughly 68°F. The positive
correlation between average measured room temperature and average survey PMV indicates that as the room temperature increases, so does the average PMV—making these two variables directly related. This means that higher average room temperatures point towards positive PMVs (warmer rooms) and that lower average room temperatures point towards negative PMVs (cooler rooms).

Figure 4.23 shows the relationship between the surveyed average PMV for specific classes and the change that occupants prefer to feel during those classes, in terms of PMV.

Figure 4.24 is a visualization based on collected survey data that describes the negative correlation between the average measured room temperature and the average preferred change in temperature.
Figures 4.25 and 4.26 compare the survey PMV to calculated PMV values using EES for different clothing insulation levels with respect to the measured indoor temperatures and relative humidity. For each PMV calculation, the MET was kept constant at 1.0 met, the air speed was 0 ft/s and the radiant room temperature was assumed to be the same as the air temperature. Figure 4.25 shows how the calculated PMV is underestimating the survey PMV. This underestimation can be easily visualized through the difference in slopes. Ideally, the clothing insulation slopes should closely resemble the slope of the $y = x$ plot, which is bolded in black below.

![Figure 4.25 The difference in slope between calculated PMV and survey PMV for different clothing insulations.](image)

Figure 4.26 further illustrates the differences in the PMV values that were calculated compared to the survey PMV. The three calculated PMV trends for the different clothing layers all follow the same trend and have similar slopes with respect to the indoor temperatures, with an increase in PMV as more clothing layers are added. With
respect to the survey PMV values, the PMV values for different clothing insulations are similar and yield similar slopes.

Figure 4.26 shows the difference in slopes between the yielded survey PMV and the model PMV with respect to clothing insulation.

There is some research that indicates that the Fanger model is not as accurate as it is thought to be. PMV-PPD model varies in accuracy based on ventilation strategies, building types and climate groups. Since the Fanger model was developed in a highly controlled environment, it does not properly reflect the true conditions students may feel in a classroom. [38] Student acclimation time and adaptative behaviors must be taken into consideration; one hour for lecture classes may not be enough for students to acclimate to room conditions and so that affects accuracy of the PMV model. Additionally, the inability for students to exercise adaptive behaviors leads to greater thermal environment dissatisfaction. [38] Figure 4.27 below shows the comparison between the Fanger PMV model and the simpler model developed by researchers at UC Berkeley. The
The graph on the left shows the simpler model and the graph on the right shows the current PMV model. The simple model was developed using only air temperature as the input parameter while the current PMV model uses air temperature, radiant temperature, relative humidity, air speed, clothing insulation, and metabolic rate. Clothing insulation of students is likely not the issue; rather, the radiant temperature of the classroom is warmer than it is thought to be, which leads to greater student discomfort. Although the overall prediction accuracy for the new model is only 1% more accurate than the current model, it indicates that there are alternative approaches for more accurate model development.

Figure 4.27 Comparison of simple model and Fanger PMV model. Adapted from [38].

Figure 4.28 shows the relationship between average measured CO2 and how it could be influenced by student stress levels. There are several interesting data points which suggest that more survey data is needed to accurately determine a relationship between the two variables. In Figure 4.29 the data indicates that the more students there are taking a quiz/exam, the higher the average CO2 concentration is in that room. None of these instances of higher CO2 concentrations occurred in 38-220 or 38-219 in the late
afternoon when we know that the CO₂ concentration were high, so these data are independent of the known ventilation issue discussed in Section 4.3. Adding more students, the majority of whom are stressed, would only increase the average CO₂ concentration in the room, which is verified with the idea that since a quiz/exam is often stressful, and humans tend to naturally breathe much faster when stressed out. [39] However, if the ventilation was adequate for the data that was taken, then the CO₂ concentration would not increase in this way with an increase in the number of students. To further solidify this relationship and draw accurate conclusions, more data would be needed. There are a few instances of very high CO₂ concentrations below. From 1,000 – 2,000 ppm there are complaints of drowsiness and poor air quality. From 2,000 – 5,000 ppm there are complaints of headaches, sleepiness, fatigue, stuffy air, poor concentration, difficulty to pay attention, increased heart rate and even slight nausea. Figure 4.30 shows the measured CO₂ concentration vs the number of students in the room. The three datapoints that are between 40 and 50 students have CO₂ concentrations below 1,000 ppm. The fact that the CO₂ concentrations are below 1,000 ppm is likely indicative of the data being taken for larger classrooms or that there is adequate ventilation. On the other hand, the few other datapoints that exceed 1,000 ppm are likely due to inadequate ventilation.
Figure 4.28 The comparison between average measured CO$_2$ and its effect on average stress gathered from surveys.

Figure 4.29 The relationship between the average measured CO$_2$ and the number of students taking a quiz/exam. It is expected that the measured CO$_2$ increases with respect to the number of students taking a quiz/exam, given that students begin breathing quicker when stressed and under pressure.
Figure 4.30 The measured CO$_2$ concentration from surveys with respect to the number of students in the room.
Chapter 5

Conclusions and Future Work

This chapter discusses conclusions that can be made based on the results collected in Chapter 4, as well as future work that can be completed to further support the discussed conclusions or potentially make new conclusions.

Students are less likely to feel neutral with room conditions at higher temperatures than they are at lower temperatures. We found positive correlations between the percentage of students not neutral with room conditions, outdoor temperature and survey PMV. Based on the data, it can be concluded that higher outdoor temperatures lead to a higher percentage of students not happy with indoor conditions. This is because when students are cold, they can more easily control how they feel in classrooms by adding more layers; however, if students are already feeling too warm while wearing very light clothing insulation, there is nothing else they can do to cool themselves off. Classrooms that reported positive average PMV (warmer than neutral classrooms) generally tend to have higher percentages of students who are unaccepting of the room’s thermal comfort, as opposed to classrooms that reported negative average PMV (cooler than neutral classrooms). Additionally, the relationship between indoor air temperature and student stress levels was explored. Based on the data collected, no correlation can be determined between indoor air temperature and student stress levels. This means that student stress levels are not dependent on the indoor air temperature and rather are likely influenced by other factors than room air temperature. On the flip
side, increased occupant metabolic rates due to stress are not influencing indoor air temperatures.

Based on the results of 744 student surveys, it was concluded that students prefer to feel cool in rooms rather than feel warm. PMV and indoor air temperature are directly related variables. The lower the indoor air temperature, the greater the magnitude of the PMV in the negative direction, indicating students will feel colder. The higher the indoor air temperature, the greater the magnitude of the PMV in the positive direction, indicating students will feel hotter. We found strong negative correlations between PMV and PMV change preferred, and room temperature and preferred change in temperature, respectively. This means that when the room air temperature is high (positive PMV), the occupants prefer to feel cooler in the room (negative PMV change), which makes sense. However, there are also several recorded instances of the occupants on average feeling cool in the room but preferring for the room to feel even cooler. There are 28 total classroom survey datapoints, of those 28 datapoints, 25 classes on average preferred for the room to be cooler while only 3 classes on average preferred for the room to be warmer.

We compared the results from the survey to predictions using the Fanger PMV thermal comfort model for different clothing insulations. We found that the PMV model underpredicts how people should be feeling in the classroom. Conditions that “should” be considered comfortable were typically too warm for the students. Another research confirms that the Fanger PMV model is not as accurate as it is thought to be. According
to researchers from UC Berkeley, PMV is accurate predicting thermal sensation only 34% of the time. Most of the parameters used to calculate PMV are challenging to measure and estimate in real conditions, so a simpler model with less parameters could pose its benefits. The researchers concluded that a simple model utilizing just air temperature as its input parameter can provide more accurate results than the Fanger PMV model. This conclusion is based on just one model that was developed that proves that alternative approaches can be more accurate and that those alternative approaches should be explored. Although this increase in accuracy between the simple model and the Fanger PMV model is marginal, there is only an increase of 1% in accuracy, it shows that the Fanger PMV model is not as accurate as anticipated and that better solutions can be developed for predicting thermal comfort. [38]

Results indicate that more data is needed to draw definitive conclusions about how CO₂ concentration is affected by student stress levels and the number of students taking a quiz/exam. Data show that at 17 students or more, the CO₂ concentration exceeds 1,000 ppm. From 1,000 ppm – 2,000 ppm there are complaints of drowsiness and poor air. At 2,000 ppm – 5,000 ppm there are complaints of headaches, sleepiness, stuffy air, poor concentration, loss of attention, increased heart rate, and at times slight nausea. Thus, CO₂ concentrations higher than 1,000 ppm will affect student performances on exams. Since the acceptable air quality for a room should not exceed 1,000 ppm, especially during COVID—when COVID is mostly transmitted through CO₂—a conclusion that can be drawn is that there needs to be a greater air changes per hour rate to avoid CO₂ build-up. The fact that CO₂ concentrations are exceeding 1,000 ppm is likely due to
inadequate ventilation rates. This should be further explored to rectify the issue that is seen with CO₂ concentrations increasing with respect to the number of students in class. More data should be taken to further strengthen the correlation between the two variables. Additionally, there appears to be a weak correlation between how student stress levels are affected by CO₂ presence in a room; however, more data is needed to make definitive conclusions about relationship between CO₂ and student stress levels.

Ventilation strategies for Building 38 were simulated. Models indicate that double ventilation 24/5—meaning double the minimum ventilation rate and ran for 24 hours per day, Monday through Friday—is best for reducing peak monthly average temperatures and overall contributing to a cooler thermal environment. Since results indicate that students are more accepting of colder environments than they are of warmer environments, the implementation of a ventilation strategy such as double ventilation 24/5 could help students feel more comfortable with their environment. On top of using a 24/5 double ventilation strategy, it must be considered to at least ventilate at night. Ideally, it would be best to ventilate more at night, when students are not occupying the building, (100% open air damper during the night), and then to modulate the AHU damper/amount of outside air during day based on indoor and outdoor temperatures. For example, when it is warmer outside than inside, reduce the outside air to minimum and increase it when outdoor temperatures are below the indoor temperatures.
There remains unanswered questions that should be considered for future work:

- We are aware that the damper for AHU-2 is completely open in Fall 2021; however, we are not certain if Cal Poly is also increasing minimum ventilation (the cfm value requirements from Chapter 1.3) based on ASHRAE Standard 62.1 given that students are back on campus during this time, even though COVID-19 is still a public health issue. In addition, the fans turning off at 5 PM, when there are still classes until 8 PM in the building, leading to an increase in CO₂ concentration is problematic and should be investigated.

- How impactful is clothing insulation in the early morning versus in the afternoon for occupant perception of thermal comfort? How influential is the weather forecast in determining the clothing people wear and the subsequent thermal comfort sensations in the afternoon compared to the morning?

- Can we use simpler models to predict thermal comfort more accurately and collect more student surveys to verify their respective thermal comforts?

- Do we need to consider changing the HVAC system outputs for the setpoint temperatures?

- Do CO₂ concentrations exceeding 1,000 ppm lead to lower performances on quizzes/exams?
Bibliography


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[36] Email Correspondence with Jessica Hunter Customer Service Manager for Facilities Management and Development, July 2020

[37] www.schedules.calpoly.edu


APPENDICES

Appendix A

DESIGNBUILDERS SETTINGs

Appendix A contains screenshots of the tabs found in DesignBuilder for various settings used for developing the model of Building 38.
Figure A.1 DesignBuilder activity tab
**Construction Template**

**Template**

**Construction**

**External walls**
- **Wall, Mass, R-13.0 (2.29), U-0.066 (0.37)**
- Project below grade wall
- Project flat roof
- Project pitched roof
- Project unoccupied pitched roof
- Project partition

**Semi-Exposed**
- Project semi-exposed wall
- Project semi-exposed ceiling
- Project semi-exposed floor

**Floors**
- Project ground floor
- Project external floor
- Project internal floor

**Sub-Surfaces**
- Project wall sub-surface construction
- Project internal wall sub-surface construction
- Project roof sub-surface construction
- Project external door
- Project internal door

**Internal Thermal Mass**
- Project internal mass
  - Zone capacitance multiplier: 1.00

**Component Block**
- Geometry, Areas and Volumes
- Surface Convection
- Linear Thermal Bridging at Junctions

**Airtightness**

**Model infiltration**

**Constant rate (ac/h)**
- 0.250

**Schedule**
- 7 AM - 10 PM

**Delta T and Wind Speed Coefficients**

**Cost**

*Figure A.2 DesignBuilder construction tab*
Figure A.3 DesignBuilder openings tab

Figure A.4 DesignBuilder lighting tab
Figure A.5 DesignBuilder HVAC tab