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Enhancing Thermal Design Education through Project-Based Learning: An HVAC Project with Real-World Data

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Abstract

This paper presents the design and analysis of a heating, ventilation, and air-conditioning (HVAC) system for a new hypothetical dormitory on campus, using project-based learning to integrate thermodynamics and heat transfer concepts in a senior level Thermo-Fluid Systems Laboratory course. The project uses real atmospheric data in the HVAC system model, requiring students to assess the system performance over a 5-year period in terms of energy efficiency, cost-effectiveness, and environmental impact, fostering deeper understanding and application of thermodynamic concepts using real-world scenarios.

The emphasis of the design process is on psychrometric processes and modeling heat transfer within the building to determine the heating and cooling loads throughout the year. Students are provided with R-values for the walls and windows, target ranges for building temperature and relative humidity, a simulated thermal source from dormitory occupants and their electronics, and 5-years of real-world temperature and humidity data (averaged daily) for the dormitory's location. As part of the design exercise, students are asked to model the HVAC system for each day for the 5-years, including heating, humidification, cooling, dehumidification processes, and return air mixing that complies with ASHRAE standards. The energy analysis of the system can be completed using component models for the heating and cooling coils, allowing students to evaluate the electrical power/energy required to operate the HVAC system on a per day, and annual basis. Using the local cost of electricity, the energy requirements of the system can be converted to an annual operating cost. As part of the design, students are asked to consider two cases 1) normal operations where air recirculation is allowed, and 2) a pandemic case study where no recirculation is allowed. These two cases allow students to compare the costs (energy and monetary) of the system design and suggest improvements to the overall design applying concepts from all their energy courses. By engaging in this comprehensive design task, students develop critical thinking, problem-solving, and collaborative skills. Furthermore, the integration of cost and environmental factors in the design process underscores the importance of sustainable engineering practices using real world data. This pedagogical strategy not only enhances technical proficiency but also prepares students for the complexities of professional engineering practice by exposing students to professional standards. This project demonstrates the effectiveness of project-based learning in developing practical engineering solutions and enhancing student engagement in energy systems design.

We have some initial, generally positive, anecdotal data about students' perceptions of the project. However, we are planning on constructing a more formal and detailed survey to obtain more detailed information from students. In addition, we are also looking to investigate the impact of the project on students' satisfaction of the course learning outcomes.

Background

There is considerable evidence to the benefits of students working through open-ended complex projects in engineering education [1]. Projects allow students to engage with real-world problems, work collaboratively in teams, synthesize concepts from multiple subject areas to develop a solution, and choose an optimal solution from an assortment of viable solutions. These attributes are all consistent with modern professional engineering practice [2]. Furthermore, to receive ABET accreditation, programs must also be able to demonstrate that their students have "*an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors*" [3]

There are a multitude of opportunities to integrate real-world projects into the undergraduate mechanical engineering curriculum to help students engage more deeply with the course content. For instance, several instructors have described the use of a bridge design project in statics courses to help students solidify their understanding of equilibrium concepts and truss analysis techniques [4], [5], [6]. In instrumentation and controls courses, examples of projects include students designing and assembling a custom air-speed measurement device [7], and experimentally determining the system parameters such as natural frequency, damping ratio, etc. of a mechanical system [8]. Finally, the thermal-science courses such as thermodynamics, fluid mechanics, and heat transfer provide students with the ideal venue to grapple with problems focusing on global climate change and alternative energy sources. For instance, in a thermodynamics course, students can be tasked with optimizing an existing fossil-fuel based power plant to become more energy efficient [9], [10], [11] or redesigning it into a combined-cycle system [12]. Another example revolves around the topic of high-performance buildings [13], which has received considerable attention because the construction and operation of buildings account for a significant portion of total greenhouse gas emissions into the atmosphere [14]. As a result, more energy efficient buildings through greener building construction materials and more energy efficient building mechanical systems can significantly reduce the human impact on the environment [14]. Additional advanced energy projects can also address renewable energy topics [15] or heat exchangers [16].

Projects based around real-world problems also permit opportunities to incorporate real-world data in the analysis and design phases. Depending on the type of problem and system, these data sets can be large, incomplete, and exhibit extremums. Such attributes are largely in contrast to data students often work with in problem sets where the data is "clean" and well-defined leading to a straightforward final solution. In addition, the presence of extremums in the data provides unique opportunities for students to develop solutions that will operate reliably at conditions deviating substantially from the mean. Finally, due to the size of these data sets students can get additional experience applying computer programming skills they learned earlier in the curriculum to automate the integration of these large data sets into their models and designs.

In this paper, we describe a project assigned to fourth-year mechanical engineering students in an applied thermodynamics course where they are tasked with performing the preliminary design calculations for a heating, ventilation, and air-conditioning (HVAC) system for a new fictional campus dormitory that was going to be built. As part of the analysis, they must determine the heating, cooling and humidification requirements every day for a single year using historical local temperature and relative humidity data averaged daily over the past five years. The project provides an ideal platform for students to synthesize concepts from heat transfer and psychrometrics while incorporating economic considerations and utilizing computer programming tools to perform the design calculations–a combination traditionally lacking in most homework/textbook problems.

Project Description

Logistics

The project, described in detail below, was assigned to mechanical engineering students in a fourth-year three-credit applied thermodynamics course taught at a primarily undergraduate institution (PUI) situated in the Midwestern United States. The pre-requisites for the course include two quarters of thermodynamics, one quarter of fluid mechanics, and one quarter of heat transfer. The credit distribution for the course is 2-2-3 which means that the course consists of two fifty-minute lectures and one two-hour lab each week. The lectures discuss the application of the 1st and 2nd laws of thermodynamics to reciprocating engines, air-water vapor mixtures and HVAC systems, and chemically reacting systems, and concludes with a discussion of heat exchanger analysis and design.

During the laboratory sessions, students worked in small groups to experimentally investigate the performance of a vapor-compression refrigeration cycle, a spark-ignition engine, a psychrometric chamber, a residential combined heat and power (CHP) system, and an air-water heat exchanger. Students performed the experiments, collected data, and summarized their findings through technical presentations and reports. In addition to the experiments, they also completed two design projects in their lab groups, the second one being the HVAC project described below. Students were given three weeks to complete the project and to present their results in the form of a written report. The lab groups ranged from two to four students depending on the term with an average group size of three.

Project Overview

This project tasks students with the design/analysis of a HVAC system for a proposed new dormitory on campus accounting for the thermal loads on the building over a 5-year period. The purpose of this project is to provide a real-world example of thermal engineering that incorporates heat transfer resistive modeling, thermal load modeling, psychometrics, and some energy optimizations. Additionally, the project is designed to help students have a better understanding of the scale of energy needed for large equipment, and the environmental and monetary costs associated with these systems. Lastly, we aim to have students think critically about the proposed thermal design and suggest improvements by having students determine components or values that are not ideal for the given design. For this reason, we have purposely selected several non-ideal components/values (such as flow rate or heating equipment) that students must identify and then suggest improvements in the later parts of the project.

To construct the building thermal model, students are given several specifications and constraints about the building. The new dorm is estimated to have a footprint of 150 ft by 100 ft, with a height of 156 ft. To maintain a comfortable working environment for students, the air inside the dormitory is to be always kept at 72°F with a relative humidity between 45% and 60% throughout the year and the total volume of the air space must be completely refreshed (circulated) at least four times per hour to ensure a comfortable environment is maintained. This deliberately corresponds to a larger flow rate than needed so that later in the project students could propose modifying it to improve the system performance. These conditions establish the thermal conditions inside the dormitory, the flow rate of air in the HVAC system, and provide a consistent starting point for the heat transfer modeling.

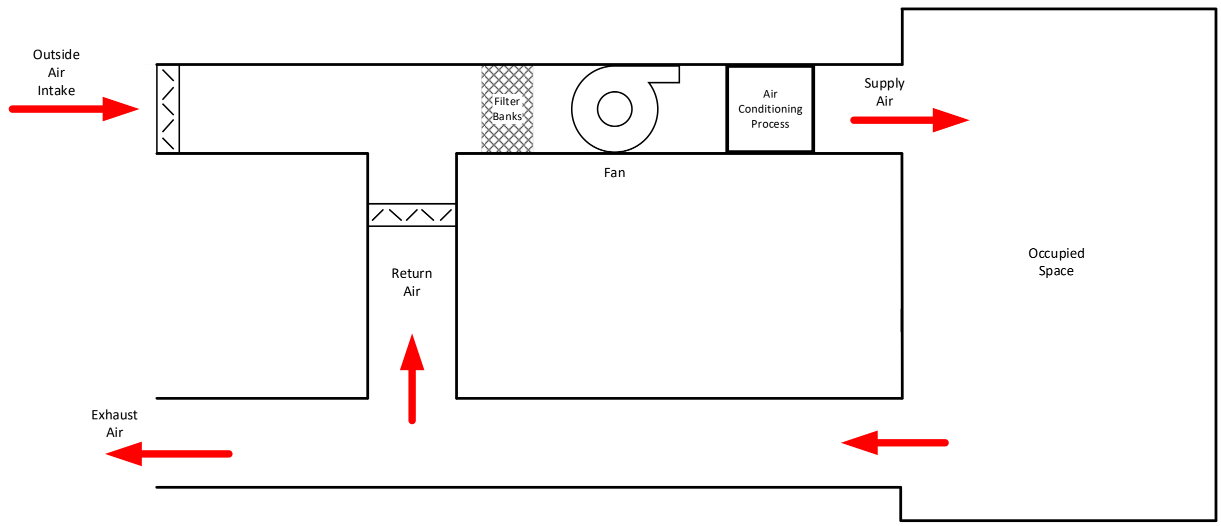

Figure 1: A schematic of the dormitory with the attached HVAC system. The HVAC system also includes the ability to have return air mixed with the outside intake air.

To estimate the thermal loads of the building, students must account for the occupancy of the dormitory and thermal losses through the building walls. The building is designed to house 600 students, and each student will generate 110 W of heat continuously (basal metabolic rate ~2270 kcal per day, an estimate value based on a somewhat active student [17]) in addition to 150 W of heat from electronics, providing a total of 260 W of heat per person. Additionally, each person releases 900 mL of liquid water per day via respiration and perspiration that evaporates into the air. For modeling simplicity, it is assumed that students stay in the dormitory using their electronics for the full 24 hours per day. Other sources of energy or water are noted but not considered as part of the model to avoid overcomplicating the project. To account for heat losses and gains through the walls, students are given that the exterior walls have an R-value of 40°F-ft^2/(BTU/hr) and that the long walls (150 ft side) have double paned windows with an R-value of 1.75°F-ft^2/(BTU/hr) that account for 20% of the overall surface area. The heat losses to the surroundings are assumed to occur through the four side walls and the roof (floor losses are neglected for simplicity). The external air flow around the building results in a convective heat transfer coefficient of 150 W/m^2-k. It is noted that the size values were selected based off an existing dormitory building on campus, and R-values were approximated using regional appropriate attic insulation values–which are overestimates of the side wall values [18]. The overestimation of the R-values was selected to provide sufficient building insulation, and to try to prevent students from using more insulation for one of the later improvement deliverables. The building size, building purpose, occupancy, energy usage, and R-values can be adapted for future iterations of the project.

To size the HVAC components, students are asked to consider the psychrometric processes that need to occur to achieve the desired dormitory conditions. The HVAC system consists of a heating coil, a cooling/dehumidification coil, and a humidification liquid water spray. The heating is provided by an electric resistance coil, while the cooling coil is part of an air-conditioning system with a fixed COP_R of six.

Additionally, as part of the HVAC design, students are given that the dormitory meets the standards for ASHRAE 62 standard for class 1 air [19]. This standard allows for the supply air to be made up of up to 85% recirculated return air (note: the standard percentage is defined by volume, but for calculation simplicity students are advised to assume the percentage is on a mass basis). This adds a mixing chamber upstream of the heating/cooling coils that the students must now consider. As part of the project, students are only told that they must comply with the standard in their attempt to produce an energy efficient HVAC system, allowing them to explore the impact of varying the mixing percentage.

To facilitate the return air discussion, students are given two cases to consider, 1) normal operation where they may set the fraction of the return air (0-85% based on ASHRAE 62 Standard [19]) each day, and 2) a pandemic case where the air is contaminated (class 4 air) and cannot be recirculated. Students are asked to compare the performance of the building under each case and determine if the building should be designed to be able to house students during a future pandemic. As part of this process, students are only given that the air is now considered class 4, and they must review the standard to determine what impact this classification will have on the system, with class 4 air eliminating recirculation. The pandemic case provides an illustrative example of when the use of return air is no longer allowed due to the presence of an airborne contaminant and allows the students to investigate the impact of this operating mode on the operational cost. Additionally, this portion of the activity was designed to have students understand the importance of using engineering standards when making engineering decisions.

Weather data

To allow students to simulate the dormitory over a range of expected weather conditions, a data set consisting of the daily averaged temperatures and relative humidities was given to students. The weather data was scraped from the Weather Underground using the Wundermap [20] to select a local weather station near the location of the proposed dormitory. The Weather Underground Wundermap provides a map of privately owned weather systems that upload the weather data (temperature, relative humidity, precipitation, solar flux, wind speed, etc.) in up to 5-minute increments, or consolidated average daily values. The map has weather monitoring stations across the world allowing the location of the building and the data set to change from term to term. The data scraping was completed by the instructor and the students were given the compiled data set.

For the given project, students were given 5-years' worth of data for their analysis. This dataset is shown below in Figure 2, illustrating the seasonal effects and in Figure 3, which plots the data on a psychrometric plot relative to the dormitory design conditions. The decision to include 5 years' worth of data was made to allow for year-to-year variations to be observed, and to introduce students to a large dataset that will take time to analyze and troubleshoot. Additionally, the large dataset has an increased probability of having "extreme" weather conditions that would need to be considered.

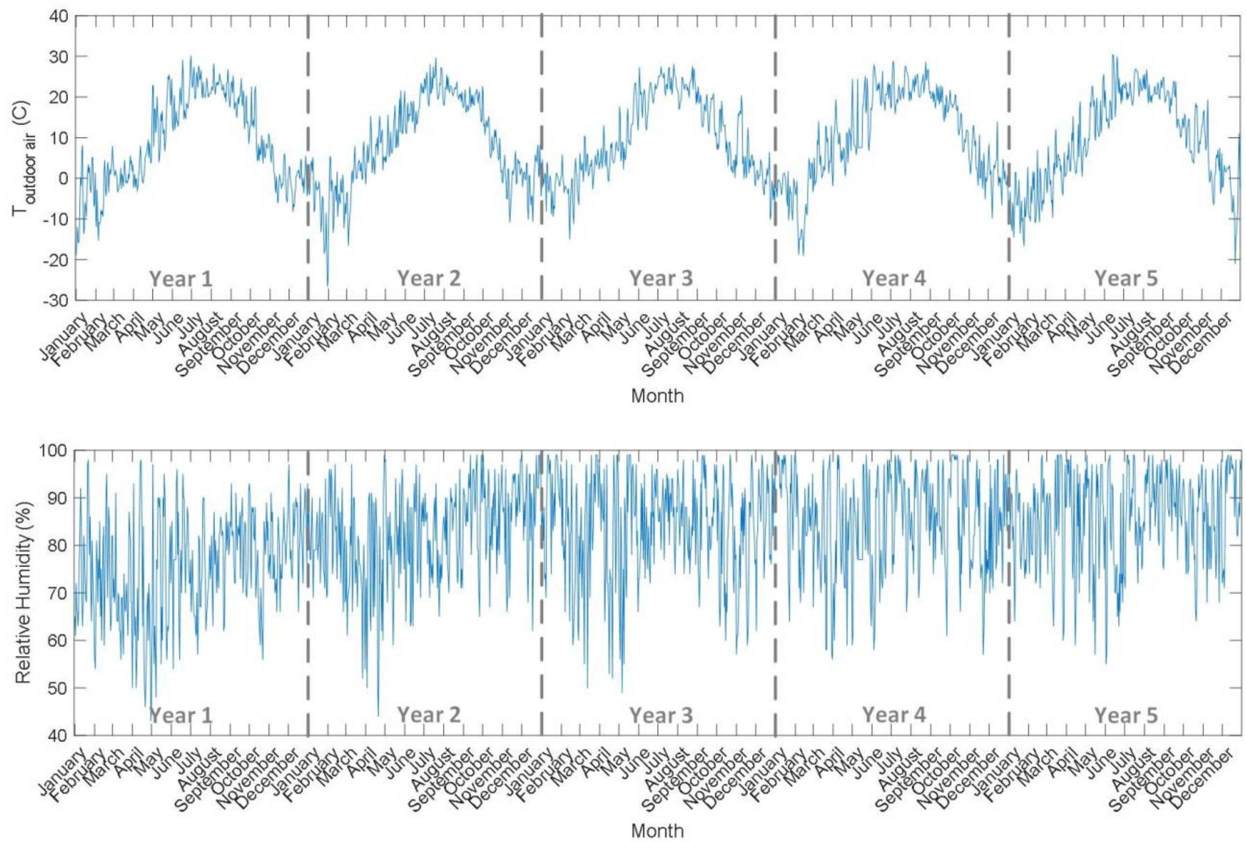

Figure 2: The average daily temperatures (top) and relative humidity (bottom) at the proposed dormitory location from 2018-2022. Seasonal temperatures are observed in the top figure over the 5-year period, capturing a few “extreme” weather days, such as the cold dip in January 2019. Relative humidity values show less seasonal dependance, but it is noted that the proposed dormitory location is near a large body of water, so a higher relative humidity value is expected throughout the year.

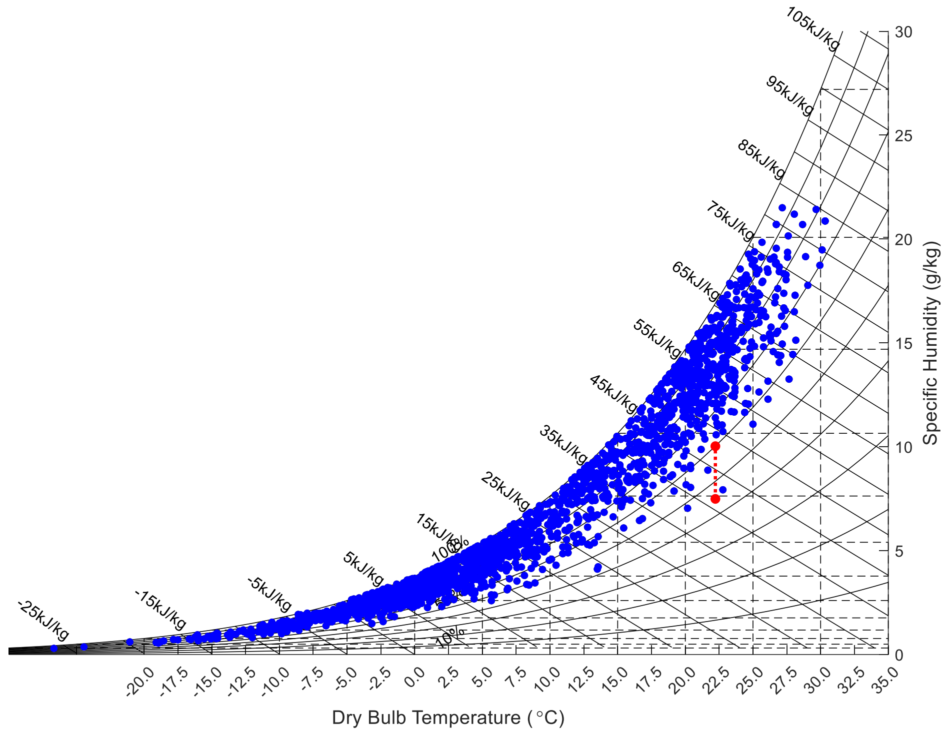

Figure 3: The ambient weather temperature and specific humidity (blue markers) for 5-years (2018-2022) at the dormitory location plotted on a psychrometric chart. The red markers indicate the defined range of acceptance for the room. The psychrometric plot was generated using the SI Psychrometric Chart script from the MATLAB Central File Exchange [21], [22]

Computational Tools

To accommodate the large weather data set (~1826 data points for a 5-year dataset), students are encouraged to use MATLAB [21] to complete the repeated calculations necessary for the deliverables. Additionally, students are given access to a MATLAB-based psychrometric calculator function [22], which is freely available through the MATLAB file exchange. The calculator allows students to define two known psychrometric properties (or three if the total pressure is not at one atmosphere) to calculate the remaining psychrometric properties. This calculator is recommended to students to reduce the need for steam table lookups and allows students to focus on the system operation and examine a large number of weather conditions.

Student Deliverables

The primary deliverable for this project is a formal report (completed in groups) that documents their analysis and the requested deliverables. The deliverables include performing a one-dimensional steady-state heat transfer (resistor) analysis of the building, an energy balance inside of the building to determine the HVAC setpoint for each day, an analysis of the humidification/dehumidification and heating/cooling loads of the HVAC system, and determining the energy, monetary, and environmental costs of operating this HVAC system on a yearly basis. The deliverables are presented to the students in a scaffolded manor, with the deliverables being grouped by the building energy analysis and the HVAC system analysis. An example of the scaffolded deliverables is included in the appendix.

Lastly, after completing their analysis, students are asked to use their knowledge of thermal systems to propose improvements to the given design and determine the impact that these changes will have on the overall system costs.

Heat Transfer Analysis

Based on the given geometry of the building and R-values of the construction materials, students are required to construct a thermal resistance network for the building, neglecting the internal wall convection resistance. There are several different ways that students can configure the resistance network with two possible solutions shown in Figure 4. Once the resistance network is complete, the overall building R-value is calculated using appropriate parallel and series resistance modeling.

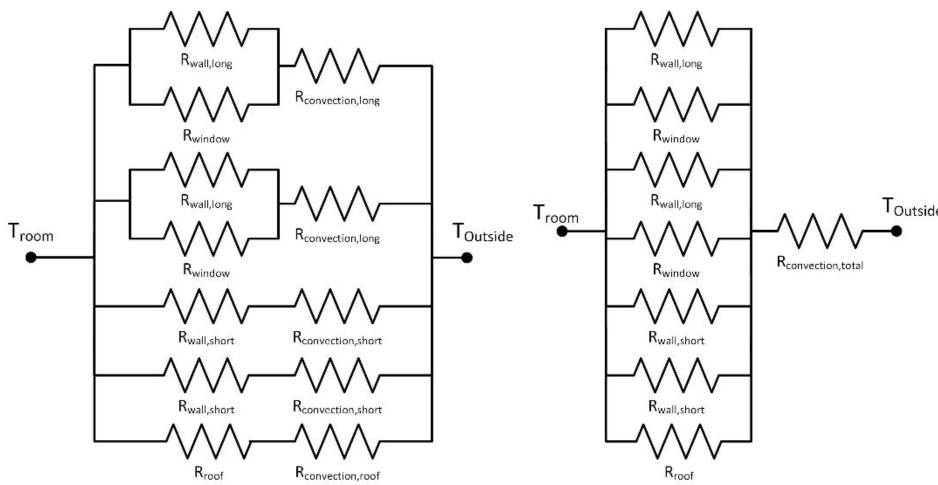

Figure 4: Example resistance networks for the dormitory building. Both versions of the resistance network will yield the same overall resistance, as the value of $R_{convection}$ will change based on the reference area.

Once the R-value of the building has been determined, students can then use the building resistance, the set room temperature (72°F) and the outdoor temperature to determine the rate of heat loss from the building using

$$\dot{Q}_{loss} = \frac{T_{room} - T_{outside}}{R_{building}} \tag{1}$$

This calculation is then repeated for each day throughout the year, illustrating how the seasons impact the energy interaction with the building. An example result of the rate of heat loss calculations for a given data set is shown in Figure 5.

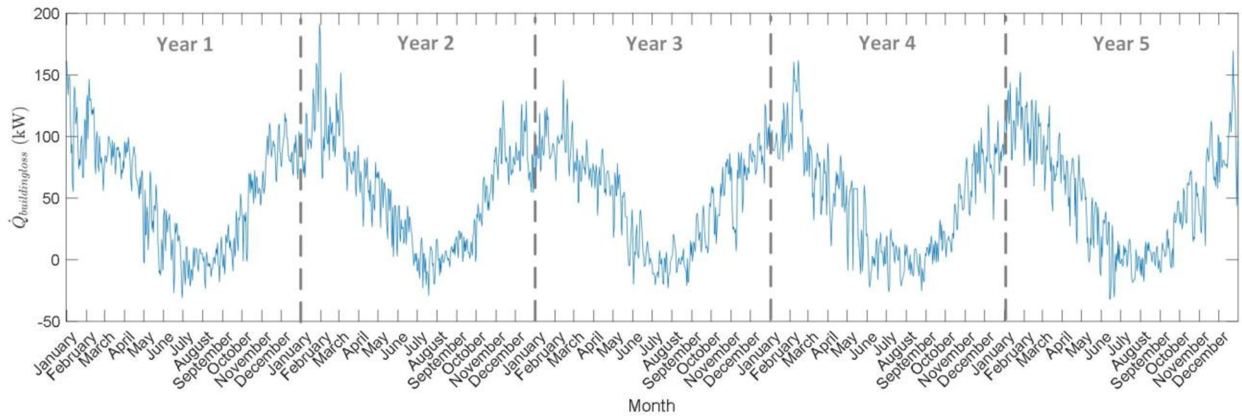

Figure 5: The rate of heat loss from the building over the 5-year period. For the given dormitory location, the ambient temperature only rises above the room temperatures in the summer months (June, July, August, September), resulting in a region where heat is transferred to the building (negative values). For most of the remaining seasons, the ambient temperature is below the desired building temperature resulting in heat transfer rate losses throughout most of the year. Note that this model neglects the solar flux on the building surface, which would decrease building losses and increase the heat gain during the summer months.

Thermal Analysis

Before the HVAC system can be sized, students must complete a thermal analysis on the building to determine the required properties of the supply air to the building, which can be determined by completing a mass and energy balance on the building shown in Figure 6. The thermal model must account for all the energy interactions between the building and the surroundings. These interactions include the energy carried in and out by the air flow, the rate of heat loss from the building to the environment ($\dot{Q}_{loss}$), and the energy addition through the metabolic activity of the students occupying the building, their use of personal electronics, and moisture addition through respiration and perspiration ($\dot{Q}_{generation}$ and $\dot{m}_{water,human}$). Choosing the moist air inside the building as the system, the conservation of mass and energy equations can be used to determine the following expressions for the moist air specific enthalpy, h_{supply}, and specific humidity, w_{supply}, at the building entry:

$$\mathrm{h_{supply}} = \mathrm{h_{return}} - \frac{\dot{\mathrm{Q}}_{\mathrm{generation}} - \dot{\mathrm{Q}}_{\mathrm{loss}}}{\dot{\mathrm{m}}_{\mathrm{air}}} \tag{2}$$

$$w_{\text{supply}} = w_{\text{return}} - \frac{\dot{m}_{water,human}}{\dot{\mathrm{m}}_{\mathrm{air}}} \tag{3}$$

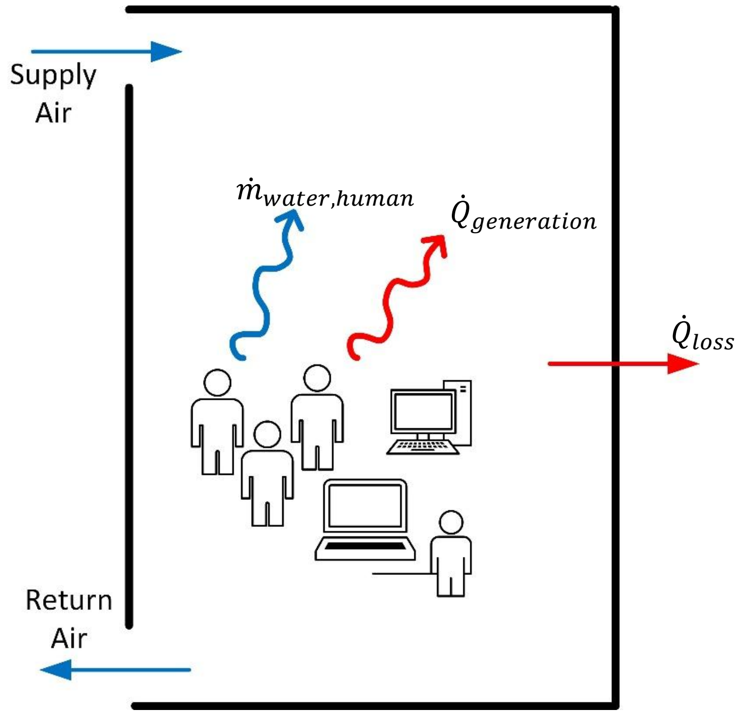

Figure 6: Energy and mass flow diagram for the building.

HVAC Analysis

After completing the building thermal load modelling and establishing the required moist air state at the room entry, the modeling of the HVAC system can occur. The HVAC system is assumed to be comprised of a cooling coil, a heating coil, and a humidification sprayer in that order. This configuration allows all psychrometric processes to occur using the same three pieces of equipment.

Before students began the HVAC analysis, we strongly encouraged students to use a psychrometric chart to identify the psychrometric processes that will occur throughout the year based on the properties of the moist air entering the HVAC system and the required outlet state, with an example annotated psychrometric chart shown in Figure 7. This helped students identify which psychrometric processes were required and help them visualize the logic-based coding solution for their code.

It is also noted that the given relative humidity range also gives students the opportunity to investigate what defined state should be targeted to reduce the overall load on the HVAC system. For example, when the ambient specific humidity is within the given range, students often think that the best option would be to only use heating or cooling, but because of the return air loop which returns additional water content this creates a feedback loop which will require them to target the upper relative humidity bound to be able to mathematically incorporate – and take advantage of the energy gains – of the return air flow.

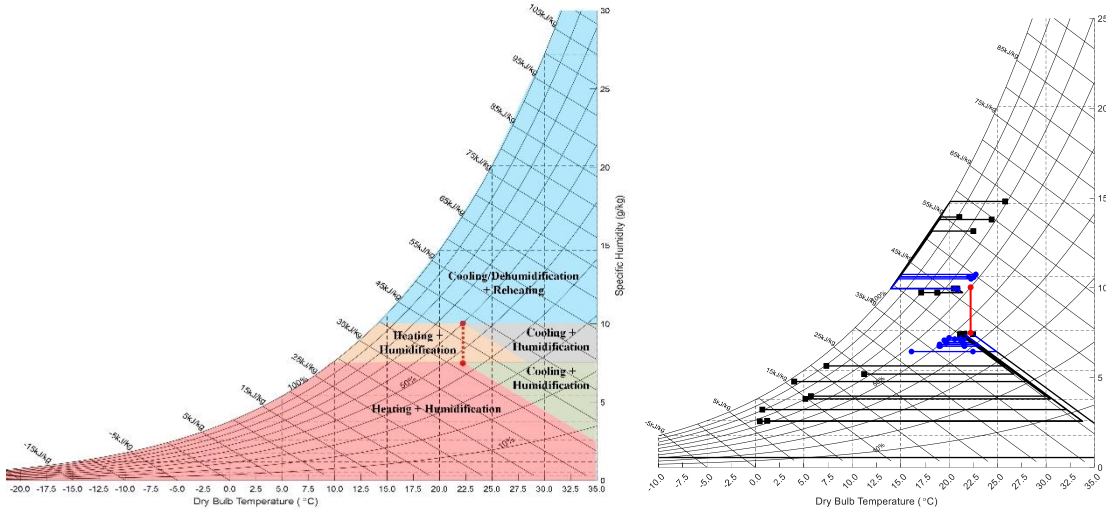

Figure 7: (Left) Annotated Psychrometric chart illustrating the decision-making process for the HVAC system when return air is used. The red markers are used to indicate the HVAC exit state based on the high and low relative humidity bounds given in the problem statement. (Right) The resulting process paths for a subset of the ambient conditions from the data set illustrating the operation of the code for the case with no recirculated return air (black) and with optimized recirculation (blue). The red lines indicate the limits on the return air for this case for reference. Not all regions were required (specifically the cooling + humidification) due to the weather conditions at the proposed locations. Lastly, note that the final exit state is different from the targeted room condition, due to the room thermal model.

Once students have identified the regions for each psychrometric process, students can develop the following energy balances for the heating + humidification process (equation (4), cooling/dehumidification + reheating process (equations (5-6), and the cooling and humidification process–which is the same as the heating + humidification but the heat transfer rate to the air will be negative.

$$\dot{Q}_{heating} = \dot{m}_{air}\left(h_{supply} - h_{mixed} - \left(w_{supply} - w_{mixed}\right)h_{water,spray}\right) \tag{4}$$

$$\dot{Q}_{cooling} = \dot{m}_{air}\left(h_{mixed} - h_2 - \left(w_{mixed} - w_{supply}\right)h_{water,cooling}\right) \tag{5}$$

$$\dot{Q}_{reheating} = \dot{m}_{air}\left(h_{supply} - h_2\right) \tag{6}$$

Here state 2 is defined as the end of the cooling process and the beginning of the heating process. This state is determined using the specific humidity of the supply air and a relative humidity of 100%. The mixed state is the state exiting the mixing chamber upstream of the HVAC system that mixes the outdoor air with the return air. The mixing state is determined using conservation of energy (equation 8) and conservation of mass (equation 9) equations using the return air fraction (RAF)–an independent variable.

$$\mathrm{RAF} = \frac{\dot{m}_{\mathrm{return}}}{\dot{m}_{\mathrm{return}} + \dot{m}_{\mathrm{outdoor}}} \tag{7}$$

$$\mathrm{h}_{\mathrm{mixed}} = (1 - \mathrm{RAF})h_{\mathrm{outdoor}} - \mathrm{RAF}\ h_{\mathrm{return}} \tag{8}$$

$$\mathrm{w}_{\mathrm{mixed}} = (1 - \mathrm{RAF})\mathrm{w}_{\mathrm{outdoor}} - \mathrm{RAF}\ \mathrm{w}_{\mathrm{return}} \tag{9}$$

Once students complete the psychrometric modeling to determine the required thermal loads of the HVAC system, they can convert the thermal loads into electrical power using equation (10) and equation (11) below for the resistance heater and the refrigeration cycle.

$$\dot{\mathrm{W}}_{\mathrm{electrial}} = \dot{\mathrm{Q}}_{\mathrm{heating}} \tag{10}$$

$$\dot{\mathrm{W}}_{\mathrm{electrial}} = \frac{\dot{\mathrm{Q}}_{\mathrm{cooling}}}{\mathrm{COP_R}} \tag{11}$$

HVAC System Results

After constructing the code, students are asked to determine the heating thermal load, cooling thermal load, the rate of water addition (humidification) and removal (dehumidification), and the power required to operate the total HVAC system over the 5-year period. As part of this process, students are asked to present two cases, 1) a case where return air is allowed minimizing the power required each day, and 2) the pandemic case where no return air is allowed. An example of these expected deliverables is shown in Figure 8.

As part of the discussion of these cases, students are asked to discuss the impacts of the return air on the sizing of the system, the monetary costs of operating the HVAC systems, and the environmental (CO_2) costs.

From Figure 8, the use of the return air significantly decreases the amount of heating and cooling required, substantially reducing the size of the HVAC system required for the building. For the given case, the return air optimized case has an average yearly energy consumption of 3,705.63 MW-h/year (~10.15 MW-h/day), while the pandemic case requires 16,140.47 MW-h/year (~44.20 MW-h/day). To relate this electrical energy requirements to a cost, students must determine the local cost of electricity by researching the regional utility pricing and estimate the CO_2 emission per KW-h for the local grid. For the given dormitory location, the current energy price is averaging \$0.17/kW-h for residential electricity [23], and is located near a natural gas power plant which is assumed to have an 0.96 $\mathrm{lb_{CO2}}$/kW-h (0.4354 $\mathrm{kg_{CO2}}$/kW-h) [24]. This results in a cost of \$630k/year and 1,613.6 metric tons of CO_2 emissions per year (~\$1,725.91 per day and 4.42 metric tons CO_2 per day) for the return air optimized case, and \$2.74 million/year with 7,028.3 metric tons of CO_2 emissions per year (~\$7,517.48 per day and 19.26 metric ton CO_2 per day) for the pandemic case.

Additionally, students often observe that power requirements of the HVAC system are generally dominated by the heating requirements, and that in the return air optimized case the largest heating load occurs during the summer months due to the need to provide reheating after the cooling and dehumidification process.

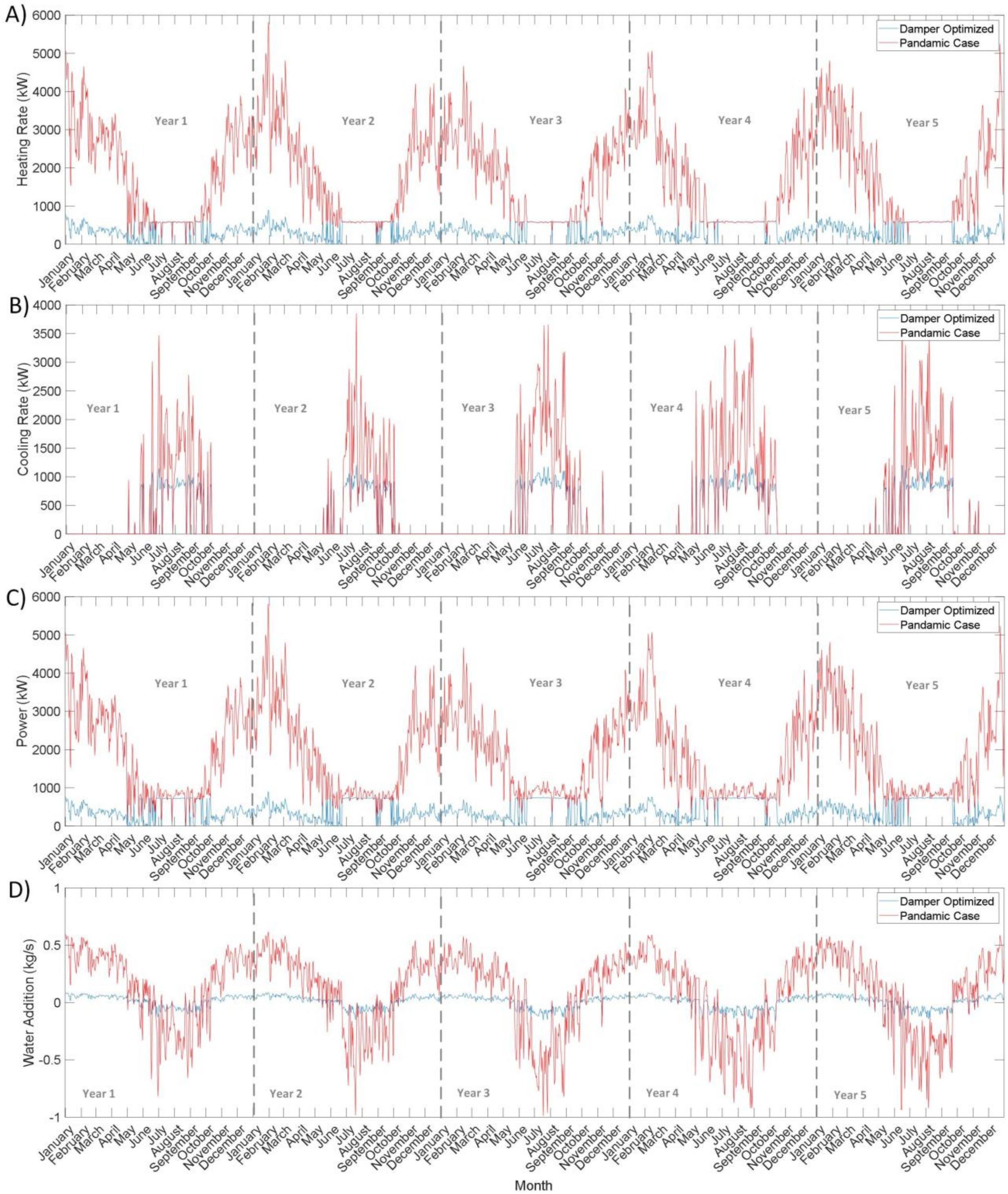

Figure 8: The HVAC system performance over the 5-year period for both the return air optimized case and the pandemic case. A) the rate of heat addition from the heating coils, B) the rate of cooling provided by the cooling system, C) the rate of water addition for humidification (positive) and dehumidification (negative), and D) the power required to operate the HVAC system.

Recommendations for System Improvement

The final deliverable asks students to reflect on their observations and the given constraints to propose at least three improvements to the system to reduce energy consumption, costs, and CO_2 emissions, and provide a discussion or updated results incorporating these changes.

While there are many possibilities to make improvement, there are several design choices that will have a large impact on the system costs, while others may have a smaller impact. Some reference improvements are presented below.

1. Replace the heating coil with a heat pump. The use of an electric heating coil is not energy efficient, and the use of a heat pump will reduce the electric power needed to operate the system. The selection of the resistance heater as part of the project design was included specifically so students could make this improvement.
2. Redesign the refrigeration system so that the heat removed during the cooling process can be partly diverted back into the HVAC air to reduce the need for reheating. This design would be similar to how a small home dehumidifier operates. The operation of a small home dehumidifier was previously covered in the course in lecture or homework.
3. Reduce the volume flow rate of the air circulating through the building, as the volume refreshes per hour is larger than the ASHRAE recommended amount. Decreasing the flow rate will decrease the amount of power/energy required by the HVAC system. The initial value was selected to let students specify this improvement.
4. The building walls could be modified to change the R-value by changing the size of the windows or the material/thickness of the walls. Changing the overall building R-value will impact the heat loss throughout the year and alter heating/cooling required from the HVAC system.
5. Change the dormitory room conditions by expanding the acceptable temperature and relative humidity range. While this may make the dormitory more uncomfortable for students, it can reduce the costs of the system operation.
6. Increase the number of students occupying the dormitory to make use of the student metabolic rate to provide heating to the dormitory during winter months.

Of the options provided, the replacement of the heating coils with a heat pump, the redesign of the cooling system, and decreasing the volume flow rate of the air will provide dramatic reductions in the HVAC operational costs. The additional points will provide a reduction in the costs but are less impactful. This deliverable was included to provide students with a chance to reflect on the design of the system, rather than just providing an analysis of the dataset, and to encourage students to recall and incorporate other thermodynamic concepts.

Discussion

The project described in the paper was administered during the Fall 2023 semester. The last deliverable, in which the students had to provide recommendations to improve the system as described above, was also used as the performance indicator to collect assessment data for ABET Student Outcome 4: "*An ability to recognize ethical and professional responsibilities in* *engineering situation and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and social contexts*" [3]. The performance indicator used to assess the student outcome was: "*Students can identify the tradeoffs involved in the selection of alternative energy sources"*. The student performance was rated on the following three-point scale:

- Exceeds expectations: Students identify at least two of the heat pump, the refrigeration redesign, or the volume flow rate reduction as part of their solutions.
- Meets expectations: Students include at least one of the heat pump, the refrigeration redesign, or the volume flow rate reduction as part of their solutions.
- Does not meet expectations: Students do not reference the heat pump, the refrigeration redesign, or the volume flow rate reduction and their proposals will only provide a limited impact on the system costs.

The performance of the 48 students that completed the project is summarized in Table 1 below:

Table 1: Student performance on the performance indicator for ABET Student Outcome 4

Exceeds expectation	**Meets expectations**	**Does not meet expectations**
7	30	11

A majority (~77%) of the students met or exceeded expectations on this performance indicator indicating that most students correctly identified at least one pathway to increase performance and cost efficiency and decrease the environmental impact of this system and proposed a solution with a significant cost impact. While this is one measure of the student performance on the project, we are currently in the process of developing a study that will allow us to quantify the impact the project had on student learning. More specifically, since the project was completed in the teams, it was challenging to use the data reported in Table 1 to assess the impact of the project on an individual student. However, from interactions with students, we can provide some anecdotes on the strengths and weaknesses of the project from the student perspective.

Students generally expressed that the project helped reinforce psychrometric concepts and illustrate how a complete HVAC system operates. Specifically, they felt the large data set enhanced their conceptual understanding of psychrometrics, as it required them to think critically about which psychrometric parameters were important in determining the required HVAC operations to reach the specified room conditions. Additionally, students often mentioned that this also helped them appreciate the use of the psychrometric chart, as it allowed them to visualize the solutions and build the code logic.

Students also appreciated that the project incorporated a cost component, as it gave them a meaningful final metric for their thermal simulation results. They felt that the cost component helped them better understand the scale of energy usage for a building and the significant impact that energy improvements—or conversely, poor design decisions—can have on the bottom line (or tuition/room and board, in the case of the dormitory). Overall, they indicated that this helped them better connect with the project and course material.

The main drawback that the students identified was that the project required a robust MATLAB code set that included several nested layers, particularly if they aimed to target the most energy-efficient relative humidity value. While all students had coding experience, not all were comfortable with the level of coding required to include all the details, with many choosing to set a single relative humidity value to simplify the coding aspect. Additionally, if the code was not well formatted (computationally optimized), the 5-year simulation could take a significant amount of time to run, with some students' programs taking between 15-30 minutes to complete. Using a well-optimized set of code could streamline this process, with the instructor's version of the code requiring 2-8 minutes to complete, depending on the computer hardware (~7 minutes using similar hardware as the students). As a result, students often expressed frustration waiting for the code to complete the analysis and suggest that a smaller data set (one or two years) could be used in place of the 5-year dataset. However, we purposely choose a large data set to provide a teachable moment, that even with advances in computational power, not all problems may have immediate solutions. Throughout their careers, students may have to simulate complex engineering systems using finite element analysis (FEA) and computational fluid dynamics (CFD) which generally do not yield instantaneous results. This necessitates the analyst to be judicious, intentional and patient when setting up and performing analysis.

We note that feedback identifying the coding challenges also correlates with feedback collected from other courses, with students expressing discomfort using code (MATLAB) during their 4th year. This issue is being addressed by increasing student exposure to coding exercises throughout the curriculum [25].

Conclusion

In this paper we present a design project that was administered to 4th year mechanical engineering students in an applied thermodynamics course. The purpose of the project was to provide students with an opportunity to synthesize concepts from thermodynamics and heat transfer and incorporate large data sets of local weather to perform preliminary design calculations for a new HVAC system for a residential hall on campus. We describe the specific deliverables articulated to the students and present some sample analysis and results as well. While there was only one "correct" answer to the preliminary design calculations that needed to be performed, the open-ended portion of the project was where the students were asked to provide suggestions, with justifications, for changes that can be made to the design to make it more energy and cost-efficient.

Since a portion of the project was used as a performance indicator to assess one of the ABET student outcomes, we present some data of student performance on this indicator. In addition, we also include some anecdotal student input on their perceptions of the project. In general, students indicated they enjoyed the project because it was motivated by a real-world problem and that it required them to synthesize concepts from multiple subject areas to arrive at a solution. However, many of them did mention finding the programming requirements to complete the project challenging, which we conclude to be indicative of the overall discomfort students feel with applying programming skills to solve engineering problems.

Moving forward we are constructing a formal survey through which we can collect data from the students. In addition, we are also exploring how to quantify the relationship between student engagement and performance on the project and its impact on the students' individual understanding of the underlying thermodynamics and heat transfer concepts.

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Appendix

Deliverables

In order to select the final design, perform the following analysis:

Building Considerations

a) Determine the net resistance for the entire building. Construct a resistance network and label all resisters. Include a clear, well formatted, complete resistance network in your report.
b) Determine the rate of heat transfer to/from the building over the 5-year time period that you have the atmospheric data. Plot the heat transfer rate or the heat transferred per day for the entire time period (use month labels not day # for axis, see canvas notes for plotting). Discuss these results.
Modeling notes: for the heat loss/gain calculations from the surroundings, you may assume that the occupied room temperature is the return air temperature.
c) Determine the Supply air temperature, relative humidity, and humidity ratio (specific humidity) for the entire 5-year time period. Plot the supply air temperature for the entire time period. Discuss these results.

HVAC Considerations

d) For each day, determine the amount of cooling and/or heating and the amount of water addition or water condensation. The average weather conditions per day for Milwaukee has been included on canvas for 2018-2022. Because MSOE is environmentally conscience, you will want to optimize your HVAC system each day for the given 5-year period.
e) Provide an annotated psychrometric chart to illustrate what HVAC processes will be used based on the properties of the incoming air.
f) Plot the heat transfer into (heating) and out (cooling) of the system over the entire year on the same figure (use month labels not day number for axis). Plot the amount of water added to the system and the amount of water that condenses per day over the entire year on the same plot (use month labels not day # for axis, see canvas notes for plotting). Lastly plot the amount of energy consumed per day (use month labels not day # for axis, see canvas notes for plotting). Also discuss any trends or observations from your results.
g) Determine the amount of electrical power that is required to provide the heating and cooling for the building throughout the year. Plot your result for the 5-year time period. Determine the total amount of energy consumed operating the air conditioning equipment (neglect fans) and discuss how much energy each component contributes to the overall energy consumed. Provide an estimate of the power needed per year and per day of operation. Discuss these results.
h) Using an external source for the cost of electricity (make sure to reference), determine the cost operating this system per year and per day. What is the environmental cost (CO_2 cost) associated with the operation of this system per year and per day? Discuss these results.
i) As part of the consideration in the design of the HVAC system, MSOE wants the HVAC system to be prepared to provide adequate ventilation during a (possible) future pandemic. For this consideration, we can assume that any contaminate is airborne (Class 4 air, ASHRAE 62.1 Standard). Due to the design constraints, additional fans and additional filter

banks cannot be added to the system. Repeat the previous parts (b-e) under this new design constraint. You can combine your plots with the plots from part c to aid with discussion. Discuss how this impacts the performance and what additional costs are associated with this constraint. Discuss these results.

j) Based off of your HVAC equipment usage in the previous parts, determine how you are going to size the HVAC equipment to ensure the design conditions can always be met. How does this compare with commercially available equipment?

k) The design of this HVAC system can be improved to reduce the costs of the operation. Describe at least 3 ways to reduce the cost and/or the environmental impact of the HVAC system, providing an explanation (reasoning/discussion) of how these changes will improve the energy utilization and the cost effectiveness of the system. This can include a redesign of the given system and/or values. If you decide to change a given parameter/value of the simulation, you should run the system with that new parameter/value to illustrate the effectiveness of this design change.