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Sustainability-Focused Project-Based Learning in a Heat Transfer Course

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Abstract

Climate change is one of the most notable societal challenges that is being pursued in the field of Mechanical Engineering. As a result, sustainability-focused design is becoming more prevalent in industry, and the same is true of Mechanical Engineering curricula. In this paper, four projects that were assigned to undergraduate Mechanical Engineering students in their Heat Transfer course will be presented and examples of student design solutions will be discussed. To ensure an authentic engineering experience, the design projects were defined based on the immediate needs of the Macoskey Center (MC) for Sustainability Education and Research at Slippery Rock University. The director of the MC acted as the customer in the engineering design process, and she was responsible for defining the project scope and requirements. All projects had to use only sustainable processes and materials during the design process. Additionally, two design concepts were required – one with the goal of optimizing cost and the other optimizing performance.

The educational goals included mathematical discussion of the mechanisms of heat transfer, design generation and selection using sustainable processes and materials, collaborating effectively in an engineering team, and technical discussion of the designs. Students were required to generate two concepts, one that prioritized performance, and another that prioritized cost and ease of implementation. Students presented their work in a written report as part of their overall summative assessment and through an oral presentation to the MC director. Overall, student project learning outcomes were achieved, and observations were noted that influenced course improvements. This work will be expanded in the future to assess educational outcomes and student perceptions of the projects, as well as extend the projects to a Capstone Design course.

Introduction

Climate change driven by global temperature rise is one of the most critical challenges faced by society today. In fact, the year 2023 was the hottest year on record according to NOAA National Centers for Environmental Information's 2023 Global Climate Report[1]. In response to the threat of climate change, professional societies such as the American Society of Mechanical Engineers (ASME) have adopted formal stances to combat its effects through sustainable engineering practices[2]. As a result, engineering educators have modified their curricula to incorporate sustainability concepts and practices into their courses. Simultaneously, educators are using active learning strategies such as project-based learning (PBL) to enhance students' educational experiences. The use of PBL allows students to engage with the course material in a creative way to generate solutions to a problem. ASME's Vision 2030 encourages this practice through several standards, including "Strengthen teamwork, communication, problem solving, interpersonal, and leadership skills" and "increasing applied engineering design-build-test experiences throughout [the] degree program[3]." In this paper, a project-based learning (PBL) strategy is presented that requires Mechanical Engineering undergraduate students to complete a sustainability-focused design project in their Heat Transfer course.

Sustainability and Project-based Learning in Engineering Education

Sustainability can be loosely defined as a framework that considers impacts across multiple dimensions, most notably economic, social, and environmental[4]. Because of this multidimensional aspect of sustainability, it can be difficult to provide a specific definition[5]. Often the discourse around sustainability, particularly in engineering, has been strongly associated with the environment due to climate change[6,7]. This can be attributed to engineers' approach to the design process from a technical perspective. As such, common sustainable strategies in ME include increasing process efficiency, using alternative energy sources and environmentally friendly materials, and considering total lifecycle effects. When considering sustainability in engineering education, these concepts in general are covered in ME courses such as Thermodynamics, Heat Transfer, Control Systems, and Sustainable Engineering. However, the level of engagement with any concept varies with the institution as well as the instructional method chosen by the instructor.

Project-based learning is an active learning strategy that empowers students to generate solutions to design problems using their creativity[8] and has its roots in improving secondary science education[9,10]. It is a popular teaching and learning strategy in undergraduate engineering education because it allows students to engage with the material at their own pace and apply their knowledge to solve a specific problem. PBL also aligns with ASME Strategy Vision 2030 by including applied design work and teamwork, communication, and interpersonal skills in the curriculum[3,11]. Several studies have proven its effectiveness as a teaching and learning strategy[12,13,14], and it can be implemented in a variety of ways[15]. These include assigning a project in a single course, assigning a joint project across multiple courses, and assigning a project to be completed over a sequence of courses.

The implementation that was used in this paper was assigning a project in a single course. Several examples of this implementation in ME curricula can be found in the literature[16],[17],[18]. Analyzing the implementation of PBL and sustainability in engineering education yields examples from several engineering disciplines, underscoring its interdisciplinary nature. Electrical engineering programs have used PBL to emphasize sustainability through energy conservation[19] and smart greenhouse[20] projects. In chemical engineering, Flynn introduced green engineering concepts into Heat Transfer problems and noted an improvement in students' awareness of sustainability concepts over the course of the semester[21]. Numerous examples of sustainability in ME undergraduate courses were presented in Tisdale and Bielefeldt's work[22]. In their work, Belu, et al. incorporated multi-disciplinary sustainable energy projects into their capstone design course[23]. Reddy et al. developed their ME Heat Transfer course to include a module tasking students with considering the social implications of thermal systems design[24]. A similar approach was used by Cooper and Mott in Thermal System and Mechanical Design courses[25]. PBL was also incorporated into thermal systems and heat transfer focused courses by Field and Ellert[26] and Megri et al.[27]. As seen from the literature, thermal systems courses are one of the common courses for sustainably focused PBL. In this paper, four real-world heat transfer projects will be introduced for their use in sustainability focused PBL implementation.

Course Description

Heat Transfer with Lab (MECH 340) is a required course in the Mechanical Engineering program at Slippery Rock University, and it was first offered in Spring 2022. It is a typical in-person lecture-based course typically taken in students' sixth semester, and it requires previous knowledge in thermodynamics and differential equations. A corresponding lab course is required to be taken concurrently, where students conduct hands-on experiments with apparatuses designed to study specific mechanisms of heat transfer. The course final grade consists of these laboratory experiments, assignments, quizzes, and a final project.

In the Spring 2022 and 2023 semesters, all students were assigned a sustainability-focused final project. The project options were consistent project options between both cohorts. This implementation was chosen to expose students to working in design teams on a long-term project, as well as introducing sustainability in a subject where it has a significant impact. It also provided students with authentic engineering design experience because they had to design to an external customer's requirements and maintain consistent communication with them.

It is worth noting that the ME curriculum at SRU does not offer dedicated Design Methodologies, Technical Writing, or Instrumentation and Measurements courses. The curriculum does have a Sustainable Energy course listed, but it has not been offered due to the size and recent establishment of the program. Because of these reasons, topics typically taught in these courses must be introduced when they are required. At the start of this project, students were given a brief introduction to a typical design process, and they were provided with a report template and rubric to aid in their technical writing. The laboratory course was used to provide them with an introduction to sensors and their use in thermal systems, including thermocouples, thermal imaging inspection cameras, and supervisory control and data acquisition systems.

Project Partnership

This project was a collaboration between the Department of Physics and Engineering and the Macoskey Center (MC) for Sustainability Systems Education and Research at Slippery Rock University. The MC is a LEED-certified 70-acre sustainability facility, seen in Figure 1, that aims to inspire and create a more environmentally, socially, and economically sustainable and just future through education, demonstration, and research[28]. Founded in 1990, the MC achieves their vision through their offering of a variety of hands-on educational programming and outdoor recreational experiences[29] and interdisciplinary research with SRU faculty[30,31]. There are several buildings on the MC property that serve a variety of educational and research purposes such as community gardens, a greenhouse, chicken coop, hiking trails, aquaponics, and indoor and outdoor classrooms.

Figure 1: Aerial view of the Macoskey Center's Harmony House (1), Harmony Barn (2), and chicken coop (3). The greenhouse is located just outside of the image on the right.

For this project, the MC director identified the facility's immediate needs relating to the field of thermal systems and heat transfer. They included various items in the Harmony House, Harmony Barn, chicken coup, and greenhouse. The Harmony House, seen in Figure 2, is the center's main building. It is a former private residence that was converted into offices and academic spaces, the latter of which can be seen in Figure 2. The base structure is over 110 years old and has undergone three major renovations, in 1988, 1990, and 2008-2010. Also, in 2009 a geothermal ground loop, seen in Figure 3, and woodstove were installed. With all these renovations, the heating, ventilation, and air conditioning (HVAC) system in the Harmony House was not interconnected as elements were added. Additionally, there is only one thermostat in the building, and it is located on the second floor at the top of the stairs. As a result, there are heating and cooling air distribution issues within the house.

Figure 2: Macoskey Center Harmony House (left) and first floor classroom space (right)

Figure 3: Harmony House geothermal ventilation ducts (left) and circulation pump (right)

The Harmony Barn, seen in Figure 4, was constructed in 1995 and is a dual use facility for the MC. It is used to store equipment used in the regular operation and maintenance of the MC on the first floor as well as serving as a secondary meeting space for outdoor education programs on the second floor. However, it has little to no insulation, which makes the indoor conditions uncomfortable for learners using the space in extreme temperatures. Its highly combustible construction and contents limit heating options for heating, thus limiting the possible design solutions.

Figure 4: The Macoskey Center Harmony Barn exterior (left) and second floor interior (right)

Also available on the MC property is a chicken coop, which is located behind the Harmony House. Previous courses' student projects have been implemented at the chicken coop, including an automated chicken feeder and automated watering system, seen in Figure 5. The watering system collects rainwater and stores it in an insulated tank to ensure a consistent water supply for the chickens. However, the watering system has not been designed to operate in freezing temperatures and poses a problem for year-round operation. In 2007, a 2.5kW photovoltaic (PV) solar array was installed next to the coop and is an available power source.

Figure 5: Chicken waterer (left) and gutter connection (right)

The final building considered in the needs assessment was the MC greenhouse, seen in Figure 6, which was installed in 2012. It is a gothic arch greenhouse with polycarbonate and silicone bead panels. When built, the greenhouse included a heater, fans, and motorized shutter for climate control. Inside the greenhouse are ceramic raised planter beds, movable shelves, and water jugs that had been used as thermal masses. A 1.68 kW PV array with battery storage is also available as a power source. However, its current functionality is not optimal to allow for growth between November and early April. There is also no system in place to track temperature and humidity variation, requiring manual adjustment of the heater and fan settings.

Figure 6: Macoskey Center greenhouse

The existing problems with the various buildings on the MC site were then translated into a set of problem descriptions and desired outcomes. These were then provided to the students of the heat transfer course for implementation in the course final project.

Project Descriptions

The director of the MC acted as the customer in the engineering design process, and she was responsible for defining the project scope and requirements. Heat Transfer students were introduced to the project options at an on-site meeting with the MC director during week 2 of the semester. During the meeting students were able to observe the project topics firsthand. The following needs were summarized by the MC director and presented as project options to the student teams. The options appeared in both the Spring 2022 and Spring 2023 semesters, unless otherwise specified.

1. Harmony Barn Insulation & Heating
    a. Current issues
        i. The barn is only able to be used May-Oct as an additional teaching and learning space. It is often too cold to be used by both MC staff and classes in the wintertime.
        ii. There is a very basic timber frame structure with insulation only on the bottom floor and large gaps between wooden panels on 2nd floor (i.e. can literally feel the wind)
    b. Desired Project Outcomes
        i. Optimize winter month usage of the 2nd floor, seen in Figure 4, by increasing insulation potential and creating sustainable heating solutions.

2. Automated Chicken Watering System Winterization (Spring 2023)
    a. Description: The MC would like to be able to demonstrate an automated chicken waterer and be able to rely on this during extended academic breaks when there is less help to take care of the chickens. Chickens need a constant supply of water, especially during the hot summer months. Additionally, in the wintertime, there must be a safe heating mechanism attached to the waterer to ensure that it does not freeze. At all times, we have about 13-15 chickens. There is electrical power access in the chicken coop. There is a need for thermal conduction into the rainwater barrel and throughout the entirety of the automated chicken waterer system.
    b. Desired Project Outcomes
        i. Finalize automated chicken waterer with short maintenance guide for year-round use.

3. Greenhouse Insulation/Heating System
    a. Current Issues
        i. We are only able to use the greenhouse until late October and then again in late April/early May, but we must start seeds indoors for germination. The ideal germination temperature range for most vegetable plants is 65-75 F.
        ii. As the greenhouse has aged, we have had more issues with heat loss.
    b. Desired Project Outcomes
        i. Optimize extended growing season usage, potentially for seed starting, as well as increasing insulation potential and creating sustainable heating solutions.
        ii. The MC would like to have late winter-spring temperature and humidity data to be able to better plan when seed starting can begin.

4. Harmony House Heating & Cooling System
    a. Current Issues:
        i. Unequal distribution of heating and cooling throughout Harmony House (i.e. too cold on 2nd floor in the winter; too hot on 2nd floor in the summer)
        ii. Woodstove heat does not effectively disseminate throughout Harmony House mostly heats the left-side (facing towards windows) of the classroom space.
        iii. Very few vents on second floor
        iv. Later additions to Harmony House are particularly cool spaces in the winter (i.e. hallway leading to stairs and Bob's Cupboard)
        v. There is only one thermostat, and it is on the 2nd floor.
    b. First Floor Only – wood stove heat distribution (Group 1)
        i. Investigate heat distribution/HVAC issues.
        ii. Collaborate with Mechatronics course students to create a temperature measurement system.
    c. Second Floor Only – general HVAC (Group 2)
        i. Investigate heat distribution/HVAC issues.
    d. Desired Project Outcomes:
        i. More effective and even distribution of warm and/or cool air throughout the house
        ii. More effective monitoring systems for understanding and automating heating and cooling needs/supply.
        iii. Overall, maximizing use of renewable and sustainable energy sources and materials and minimizing use of fossil fuel-based energy and materials

Students were then allowed to select their group members and project, and all project options were required to be chosen. Their projects also had to meet the following guidelines which were defined by the MC director. Each team was required to create a proposal that can be easily interpreted and applied by a facilities manager. The proposals were required to present two design concepts:

1. ***Performance Optimized*** – this design concept utilizes heat transfer principles and considers a formal engineering solution to the problem. Cost is a factor, but overall performance is most important.
2. ***Cost Optimized*** – this design concept utilizes heat transfer principles and considers a simpler approach to solving the problem. Cost is the most important factor, while still maintaining proper performance and improvement of the existing equipment.

Finally, the design concepts were required to align with the Macoskey Center's vision, mission, and definition of sustainability. These criteria were presented to students in the following form.

- **Vision**: The Macoskey Center aims to inspire and create a more just and sustainable future.
- **Mission**: We will achieve our vision through:
    - Education to equip people from all walks of life with sustainability skills, values, and knowledge.
    - Demonstration to inspire others through the sustainable management of our 70-acre homestead.
    - Research to advance sustainability knowledge and provide learning opportunities for SRU and the larger community.
- ***Sustainability*** **is**…
    - Meeting the needs of the present without compromising the ability of future generations to meet their own needs.
    - The integration of social, environmental, economic, and cultural systems to create thriving, inclusive, diverse, and resilient communities.

Students were assigned teams and tasked with creating their designs throughout the semester. Each team project was assessed through a final report and presentation delivered to the MC director and the class. A project grading rubric was provided for students to self-assess the quality of their work against the project expectations. Students also had access to an inspection thermal imaging camera, anemometers, and various mechatronics sensors.

There were several expected student learning outcomes from this project. It was expected that throughout the project students would be able to:

1. Use the engineering design process to produce solutions that meet specified needs with special consideration to sustainability factors.
2. Apply simplified model equations for specific applications using appropriate approximations.
3. Solve heat transfer problems using engineering calculations, simulations, and numerical methods.
4. Collaborate effectively as a member of an engineering team while considering ethical, engineering, and professional responsibilities.
5. Advance proficiency in professional communication.

Student Design Solution Examples

The project design concepts that were generated by the Spring 2022 and Spring 2023 cohorts will be discussed in further detail based on each project option.

Harmony Barn

The Spring 2022 cohort was tasked with designing solutions to enable the Harmony Barn to be used as a meeting space for outdoor classes, with a special focus on colder weather. The Spring 2022 cohort selected an overall design that considered different types of sustainable insulation, adding a wood burning stove to the space, enclosing the space to reduce heating requirements, and adding a way to access the upper area of the barn. The overall drawing of this design can be seen in Figure 7.

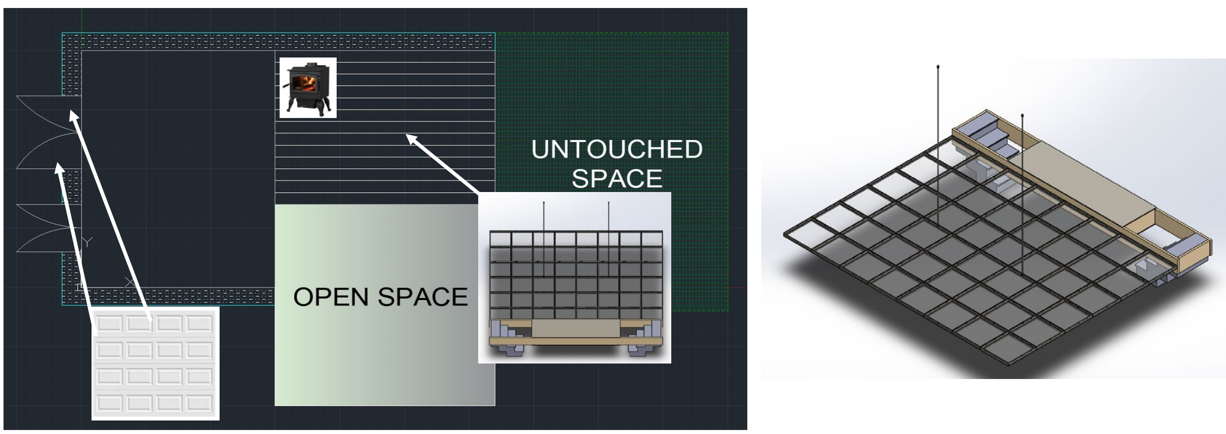

Figure 7: Harmony Barn Spring 2022 design concept floor plan (left) and custom glass ceiling (right)

For the performance optimized design solution, the team proposed replacing the barn door with an insulated garage door, a custom glass ceiling, pull-down ladder to access the upper space, a vapor seal barrier, and Rockwool insulation. This design option had an estimated cost of $23,000 not including labor. This design was selected for implementation in a capstone design course due to the quality of the proposal and the MC director's interest in pursuing it further. For the cost optimized design, the team recommended replacing the Rockwool insulation with hay, the custom glass ceiling with a clear plastic tarp, and the pull-down ladder with a basic step ladder. This design was estimated to cost around $1,200; however, the insulation performance would suffer considerably. The designs were supported with experimental data proving that Rockwool performed the best, with insulative properties improving with thickness.

The Spring 2023 cohort continued researching several sustainable insulation options such as Rockwool, soy-based spray foam, feathers, and waste denim material. They also collaborated with the Spring 2022 cohort who continued the project as a senior Capstone Design project. Experimental data were collected on all options and demonstrated that the closed-cell spray foam performed the best. An example of their experimental setup can be seen in Figure 8. Further research also showed that when considering the total life cycle of a material, bio-based spray foams are considered a sustainable option. This option was included in their performance optimized design solution, which had a total cost of $10,400. The cost optimized design solution required the suggested the use of the combination of recycled and commercially available denim insulation and had a cost estimate of $4,400.

Figure 8: Spring 2023 experimental testing of Rockwool (left), denim/feather combination (center), and spray foam (right) insulation.

Overall, the Harmony Barn student teams achieved the student learning outcomes for the final project. The engineering design process was followed, and both teams considered sustainability factors in their design generation. Their designs were also justified with simple approximations which were solved and data were presented. Each student collaborated effectively with their other team members, and their technical communication was demonstrated through their presentations and reports.

Greenhouse

For the greenhouse project, the Spring 2022 group proposed implementing a solution that would store excess heat rather than remove it. They assessed the existing greenhouse infrastructure and determined that the main mechanism of heat loss was through conduction due to no insulation. The performance optimized design consisted of adding eco-friendly bubble wrap insulation, a new insulated door, and a compost heat exchanger. This heat exchanger would use the heat generated from the composting process to heat water flowing through copper piping run along the perimeter of the greenhouse to heat the entire space. The presented design did not include any models or drawings, but rather a description of how to construct it. It had a total estimated cost of $1700. The cost optimized design replaced the heat exchanger with recycled water jugs that have been painted black to act as thermal masses. It also recommended replacing the eco-friendly bubble wrap insulation with hale bales around the exterior, tarps for the ceiling, and polystyrene foam containers to surround the planter beds. This last option did not meet the sustainability criteria set forth in the project description, due to its environmentally harmful properties. The total estimated cost of this design would be around $400. Componenta of both of these designs can be seen in Figure 9.

Figure 9: The Spring 2022 performance optimized design consisted of a compost heat exchanger (left) and the cost optimized design considered adding hay bale insulation (right)

The Spring 2023 cohort's performance optimized design required installing external heating and ventilation systems, insulation, and thermostats. This design considered electric, oil, and propane energy source options, two of which did not meet the MC director's sustainability criteria. The types of insulation considered were fiberglass, polystyrene foam, and reflective insulation. Thermostats and a ventilation system were recommended for installation, but very little information was presented on the specific system to be installed. No system parameters, mathematical approximations, or heat transfer modeling were presented to size the system. The team estimated that this design could cost up to $7000. The cost optimized design recommended installing a heat source, incorporating a thermal mass to retain heat, and adding insulation to reduce heat loss. A pellet stove was considered as well as electric and propane heaters. The proposed thermal masses were concrete blocks and recycled water jugs that were painted black. The design also recommended installation of a humidifier to maintain proper humidity levels for seed germination. Again, no system parameters, mathematical approximations, or heat transfer modeling were presented to size the system. An experiment was conducted to measure and compare the temperatures of a surface near a thermal mass and a surface with no thermal mass. Data were collected on two occasions and showed a 5°F difference in temperature. However, not all experimental conditions were defined.

Learning outcomes for the Greenhouse project student teams were partially achieved by both cohorts. The engineering design process was followed; however, both teams did not fully consider sustainability factors in their design generation. The Spring 2022 cohort's designs were justified with simple approximations, calculations, and data. However, the Spring 2023 team did not present any analytical models or approximations. Instead, they relied on one paper to justify their thermal mass design and only conducted 2 simple experiments. Each student collaborated effectively with their other team members; however, there were some students who did not fulfill all of their responsibilities. Finally, their technical communication was at times inconsistent due to missing information and data.

Harmony House - Second Floor

The project option in the Harmony House was mainly focused on the HVAC system and temperature differences on and between the first and second floors. The renovations performed on the Harmony House and the number of rooms in it introduced a layer of complexity over the other projects. The groups that focused on the second floor primarily, where the only thermostat is, used an experimental data collection approach. Both teams used thermal imaging and anemometer data to assess the temperature differences and airflow, seen in Figure 10. Between both groups data were collected and presented professionally, and the heat transfer mechanisms were analytically modeled appropriately.

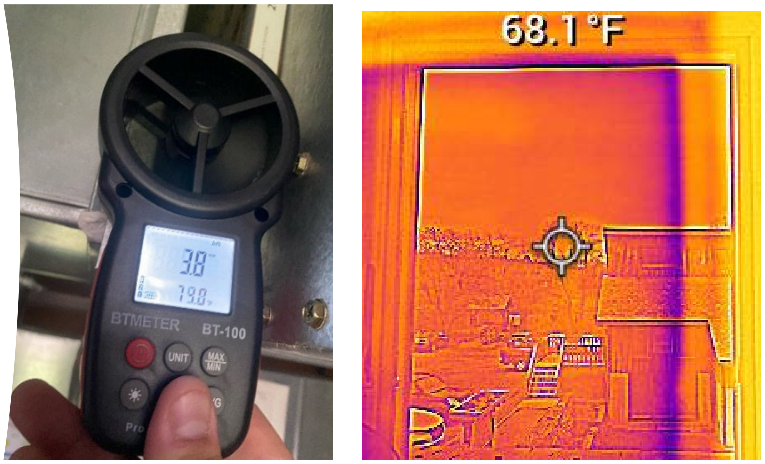

Figure 10: Experimental data collection examples for the Harmony House 2nd floor project

Their findings indicated that the windows accounted for a significant amount of heat loss and the overall air movement was insufficient. However, the experimental data collection procedures and analysis were not clearly defined. Both groups determined that the existing ventilation system was insufficient and recommended their performance and cost optimized designs, which can be seen in Table 1.

Table 1: Harmony house 2nd floor performance and cost optimized designs

Spring 2022	**Spring 2023**
Cost Optimized Designs	
• Change HVAC filters more frequently • Seal open joints on all ducts • Install curtains to prevent window heat loss. • Estimated cost: $300	• Change the air filter in the energy recovery unit. • Balance HVAC dampers based on the season. • Install a sidewall diffuser in the ductwork at the base of the stairs. • Connect a new wood burner directly to the existing ductwork. • Caulk all windows inside and outside. • Estimated cost not presented
Performance Optimized Designs	
• Install new HVAC system with updated geothermal heat pump • Resize existing vents and add new ones • Estimated cost: $40,000	• Included all cost optimized design criteria • Update the existing geothermal unit. • Estimated cost not presented

Both teams recommended updating the geothermal HVAC system as their performance optimized design, which would be the most effective way to handle all of the heating and cooling issues on the second floor. The cost optimized designs were simple and actionable, and all design choices were tied to experimental data, mathematical modeling, and reasonable approximations. The engineering design process was followed, and both teams considered sustainability factors in their design generation. Each student collaborated effectively with their other team members, and their technical communication was demonstrated through their presentations and reports. However, the Spring 2023 team did not list estimated design costs anywhere in their report or presentation. Based on these observations, the Harmony House first floor teams achieved all learning objectives.

Harmony House - First Floor

For the first-floor projects, both cohorts used an experimental approach to determine the effectiveness of the HVAC system. Thermal imaging cameras and anemometer data were again used to determine temperature distributions and air flow. The Spring 2022 group conducted an experiment running the wood burning stove for an hour then collecting data to determine temperature distribution, seen in Figure 11. They noticed that hot air was trapped near the ceiling and not being circulated back down. As a result, they recommended upgrading the entire HVAC system for the house, which is consistent with the second-floor groups' recommendation. For their cost optimized solution, they recommended installing ceiling fans in the main space and vents between the classroom space and the stairwell. This would allow air to travel towards the second floor if the door is closed.

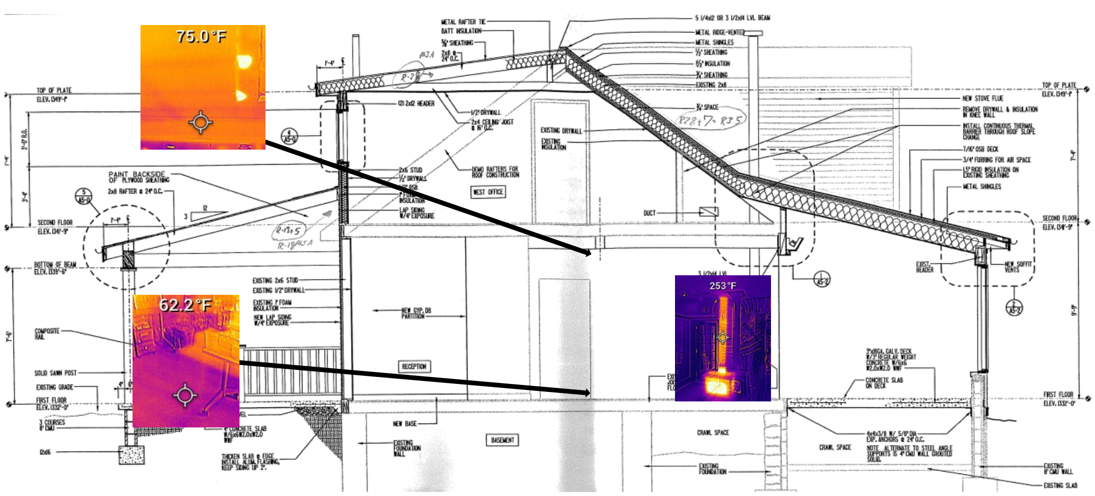

Figure 11: Spring 2022 thermal data superimposed on Harmony house computer aided drafting (CAD) drawings.

The Spring 2023 group demonstrated thorough background research into the matter, and highlighted four design concepts that were considered. For their performance optimized solution, they recommended installation of solar powered hydronic heated floors and supplemental ducts between rooms to improve airflow, seen in Figure 12. They estimated that purchase and installation costs for this design would be up to $17,000.

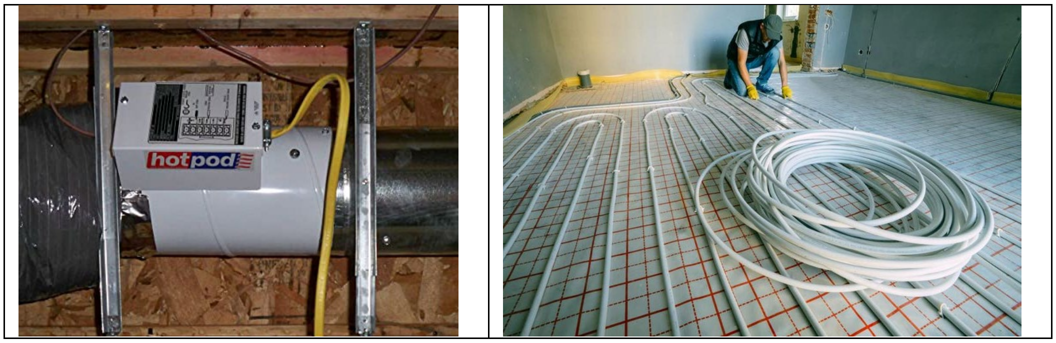

Figure 12: Spring 2023 Harmony house first floor performance optimized design solution

Their cost optimized design consisted of duct fans with convection pads that were controlled by an Arduino. This design would allow the occupants to select temperature limits on the first floor at a low cost. However, this design was simply presented, and more work would be required to mature the design. The estimated cost for this design was $150. Both designs were not supported with mathematical modeling, approximations, or specific data.

Overall, the Harmony House first floor student teams achieved the student learning outcomes for the final project. The engineering design process was followed, and both teams considered sustainability factors in their design generation. Only one team's designs were justified with mathematical models, approximations, and data, however. Each student collaborated effectively with their other team members, and their technical communication was demonstrated through their presentations and reports.

Chicken Watering System

The chicken watering system was a new project option for Spring 2023. It was a continuation of a project used in the student team's Mechatronics course. The watering system collected rainwater from the gutters of the chicken coop, which was stored in an insulated barrel. PVC pipe was connected to the barrel which dispensed water on demand into small bowls along the pipe length.

Four concepts were presented and discussed on their energy and sustainability merits, and from them the two final designs were selected. The initial concepts included a tankless water heater, electric water heater, small heating element, and a custom low-cost heating system. The design selection process was not defined, and it was not clear why these concepts were ultimately chosen. From these, the electric water heater was chosen as the performance optimized design, and the custom low-cost heating system was selected as the cost-optimized design, both of which can be seen in Figure 10.

Figure 13: Chicken waterer cost optimized (left) and performance optimized (right) design concepts

The cost optimized design consisted of heating wire added around the existing PVC pipe with insulation installed on top of that. It was also recommended that the heating wire be installed along the gutter to prevent freezing. Additionally, a 1500W stock tank heating element would be installed in the rain barrel to prevent the tank from freezing. A water temperature measurement control system was not discussed, and it is not clear if this was intended to be an always-on heating system. The estimated cost of this design was around $95. The performance optimized solution recommended replacing the rain barrel with an electric hot water tank. This solution would not require a control system since one already exists on the hot water tank, and it would also use heating wire to prevent freezing in the gutter. The estimated cost of this design was around $2,500.

The project learning outcomes for the chicken watering system student team were partially achieved. The engineering design process was loosely followed, but the design selection process was not discussed and final designs were not specifically defined. Their designs considered sustainability factors; however, they were not fully justified with mathematical models and data. Each student collaborated effectively with their other team members, but their technical communication was inconsistent and incomplete between their presentations and reports.

Observations of Student Learning

Overall, the expected student learning outcomes were observed to be achieved. Most student teams applied the engineering design process to produce sustainably minded solutions and supported their designs with mathematical models of the heat transfer mechanisms involved. Most teams also collected experimental data, although the quality of the experiments was inconsistent. Students also demonstrated the ability to gather information and functioned well as members of a team. However, there were notable areas for improvement among both cohorts.

At this point in their educational careers, students generally have limited engineering design experience due to the lack of a Design Methodologies course in the SRU ME curriculum. In this Heat Transfer project, this was evident through some groups' reliance on commercial off the shelf solutions compared to engineered solutions. This was also noted by the MC director in her debrief with the students. It was evident that students generally understood heat transfer concepts and could apply them. However, in general students did not completely discuss the assumptions, approximations, and mathematical models used to arrive at their engineering calculations. This was at times combined with a lack of supporting simulated and experimental data, despite receiving instruction on how to generate it.

The final observation made from this project is students' understanding on sustainability varied greatly among each other. This is understandable, given the multidimensional nature of sustainability. Specific examples from prior work include the suggested use of polystyrene and closed cell foam as insulation, which are not generally considered sustainable materials. However, a case can be made that these are sustainable options when considering factors such as recyclability, energy demand reduction, and total lifecycle impacts. Because of this, a dedicated lesson on sustainability and life cycle analysis will be included in the Spring 2024 lesson plan.

Planned Course Improvements

This project has again been implemented in the Spring 2024 section of Heat Transfer. Based on the above observations, the following improvements have been incorporated into the course projects.

1. Emphasizing elements of engineering design process into the project.

The engineering design process will be emphasized from the beginning when presenting the project options to the students. From there, students will pick their desired projects and are required to maintain consistent communication with the MC director and the course instructor to encourage sustained project engagement. This will help ensure that students can receive timely feedback on their work from the customer as well as solicit input from her. Bi-weekly reports will be required where students track individual task progress and can present preliminary results. Also, rather than one report at the end of the semester, intermediate deliverables are due throughout the semester. These include:

a. Problem statement and project performance specifications
b. Background research and patent search
c. Initial design concepts
d. Engineering test plan
e. Final report draft for in-class peer review

2. Incorporating CAD simulation into curriculum.

Currently, students are only instructed on how to apply computational methods to heat transfer problems with an emphasis on conduction. Previously there Based on the project observations, the course structure has been modified to include several instances of CAD-based heat transfer simulations that incorporate all three mechanisms of heat transfer. By introducing this concept mid-semester, students will learn how to create CAD simulations around the time they should be generating and selecting design concepts. Students will also be encouraged to learn through tutorials so they may obtain the skills necessary to solve their specific problem.

3. Encouraging teams to design experiments and use data to justify their designs.

One of the goals of this improvement is to help students make the connection between concepts taught in the lab and their projects. The course laboratory section will be modified to explain the different types of sensors used in thermal systems. Students will then be required to utilize them in their projects, and improvements can be suggested through the engineering test plan intermediate deliverable.

4. Instructing students on how to perform a peer-reviewed literature search.

Currently, engineering students at SRU are only required to take Critical Reading and Critical Writing, neither of which emphasize technical communication. As a result, class time will be dedicated to instruction on how to properly conduct background research and write a literature and patent search, class time will be dedicated to. The STEM librarian at SRU will join the course and highlight what resources are available to students, which sources are to be considered reliable, and how to properly cite others' work. An emphasis will be placed on how other authors present their work with models, approximations, data, and analysis. Industry codes and standards, such as those from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and ASME will also be discussed.

5. Provide a better description of sustainability

In the project description, a simple definition of sustainability is provided. This in effect places the burden on the student to learn what sustainability means for the project. To improve students' understanding of what it means to synthesize sustainable solutions and select sustainable materials, class time will be dedicated to covering how students should approach this part of the projects. Students will also receive feedback on their initial design concepts during the design review to highlight topics that both meet sustainability criteria and those that could use improvement.

Conclusions and Future Work

This paper presented four design projects that can be used to introduce students to sustainability practices in a Mechanical Engineering Heat Transfer course. The overall project outcomes were qualitatively determined to be successful. Student teams in two cohorts demonstrated their ability to follow the engineering design process to produce sustainable solutions and also to function effectively in teams. Several groups also demonstrated the ability to experimentally test their designs and analyze the results. However, a common observation was that the technical communication of the designs and results was inconsistent and at times incomplete.

The Spring 2024 projects were modified based on these observations to include adding scaffolded intermediate deliverables with the goal of improving their overall design experience, simulation and analysis, design requirement satisfaction, and technical communication. A design review has also been added to ensure students' designs are critiqued early and thus allowing them to be improved. Additionally, students will have the chance to review each other's work before final submission at the end of the semester. Finally, this project will be expanded to include a post assessment to analyze students' experiences. The projects will also be used in a sequential course PBL approach by using the final design concepts as projects in the same cohort's Capstone Design course in Fall 2024.

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