Summative Heat Transfer Project: Designing a House

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Abstract

Project- and problem-based learning have been shown to enhance learning and to provide other benefits such as improving soft skills including teamwork and communication. They can be especially effective for engineering students to demonstrate how theory is applied to real world problems. While comprehensive projects are an essential element in capstone courses, they are not used as often in traditional more theory-based courses such as heat transfer. This paper describes an example of a summative and ill-structured project to design a house which incorporates all three major heat transfer mechanisms of conduction, convection, and radiation. Project details, selected results, recommended modifications, and options for alternative implementations are provided.

Introduction

At its core, engineering is often described as problem solving (Sheppard et al. 2009). Jonassen et al. (2006) wrote,

> Practicing engineers are hired, retained, and rewarded for solving problems, so engineering students should learn how to solve workplace problems. Workplace engineering problems are substantively different from the kinds of problems that engineering students most often solve in the classroom; therefore, learning to solve classroom problems does not necessarily prepare engineering students to solve workplace problems.

The ability to solve ill-defined problems is a fundamental skill for engineers. Roth and McGinn (1997, p. 18) wrote, “Educating students to become problem solvers has been a goal of education at least since Dewey.” Jonassen (2011, p. xvii) argued “the only legitimate cognitive goal of education (formal, informal, or other) in every educational context (public schools, university, and [especially] corporate training) is problem solving.”

A common critique of the traditional approach to teaching engineering courses is there is too much emphasis on theory and not enough on practical application (Hung et al. 2003). While solving textbook problems with a single correct answer is the traditional approach to learning new engineering subjects, this should not be the only approach used. Real-world problems rarely have a single correct answer. Multiple engineers solving the same problem will often come up with different solutions. This may be because they used different data, made different assumptions, incorporated different levels of creativity and innovation, or had different preferences and biases.

More challenging problems often have less known information and require more assumptions than most textbook problems. It is these more difficult problems that engineering students have much less exposure to during the course of their studies. Based on personal experience, many undergraduate engineering students assume they will be solving well-defined problems with a single correct solution when they become working engineers. That misconception should be addressed early in their education to properly prepare them for the “real world” where there are no answers in the back of the book. The question then for engineering educators is how best to do that.

A general approach that has gained much attention is active rather than passive learning. Two such active approaches are called *project-based learning* (PjBL) and *problem-based learning* (PbBL). Prince and Felder (2006) defined PjBL as learning that “begins with an assignment to carry out one or more tasks that lead to the production of a final product – a design, a model, a device or a computer simulation. The culmination of the project is normally a written and/or oral report summarizing the procedure used to produce the product and presenting the outcome.” They defined PbBL as where “students are confronted with an open-ended, ill-structured, authentic (real-world) problem and work in teams to identify learning needs and develop a viable solution, with instructors acting as facilitators rather than primary sources of information.” The key difference between PjBL and PbBL is “the emphasis on project-based learning is on applying or integrating knowledge while that in problem-based learning is on acquiring it.” Felder (2004) noted students typically work in small self-directed teams to solve problems in PbBL.

The benefits of PjBL and PbBL are well-documented. A meta-analysis of 35 studies found a statistically significant effect that PbBL improved student attitudes, opinions, mood, and class attendance compared to traditional instructional methods (Vernon and Blake 1993). Research has shown students acquire more skills and retain knowledge longer that have been acquired by PbBL compared to conventional learning (Duchy et al. 2003). In particular, students often acquire enhanced professional problem-solving skills through PbBL (Perrenet et al. 2000). Field and Ellert (2010) described semester-long projects in a fluid/thermal design course and a thermodynamics and heat transfer course and found increased engagement and ownership from PjBL. Van Wie et al. (2011) described how projects can promote team building. Mills and Treagust (2003-2004) noted students often have a better understanding of the application of their knowledge to real problems which are often more complicated than what they are used to solving. Depending on the project, students may also get to employ some creativity and entrepreneurship (Heitmann 1996).

Many of the required ABET (2015) student outcomes are typically addressed by comprehensive semester-long team projects:

- (a) an ability to apply knowledge of mathematics, science, and engineering
- (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
- (e) an ability to identify, formulate, and solve engineering problems
- (g) an ability to communicate effectively
- (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

There is increasingly more emphasis on including smaller and less comprehensive projects in traditional engineering courses to also meet some of these student outcomes which is what has been done here.

A semester-long design project was included as one of the requirements for a heat transfer course in the spring 2017 semester. The textbook was *Heat and Mass Transfer* by Çengel and Ghajar (2015). According to de Graaff and Kolmos' (2003) PjBL classifications, this project was a task project which is "characterized by a very high degree of planning and direction on the part of the teacher (teacher objectives) involving a large task that has to be solved."

The purpose of this paper is not to assess the merits of either PjBL or PbBL, but to give a specific example of a comprehensive project that could be used in a heat transfer course that incorporates mostly PjBL and some PbBL. While a few examples of non-comprehensive team-based projects in a heat transfer course were found in the literature, only one example of a comprehensive semester-long ill-structured project was found. An example of the former is a heat transfer course that included 5 smaller team-based projects: ice rink floor, electronic chip cooling, welding, internal combustion engine valve modeling, and plastic thermoforming (Newell and Shedd 2001). Another example is a heat exchanger design, build, and test project based on a significant portion of a heat transfer course where the problem was well-defined (Anderson 1992). An example of the latter that included comprehensive semester-long projects was found for a thermal-fluid systems course rather than a purely heat transfer course, where not all of the projects required significant heat transfer analysis (Schmidt et al. 2003).

For the project described here, there were 19 students in the class divided into 4 teams determined using CATME (2017) which is a web-based tool that uses best practices to assemble teams according to how students answer a set of questions (Layton et al. 2010). The class had 17 seniors and 2 juniors which included 6 females and 13 males. While the main purpose of the project was to have students show they could apply multiple aspects of heat transfer theory to a real-world problem, it was also designed to help them improve teamwork and communication skills. It was mostly a PjBL with a smaller component of PbBL that required students to research and apply new information to solve an ill-structured problem.

Project

Learning Objectives

There were several learning objectives for this comprehensive project. The first was for students to demonstrate they could apply heat transfer theory to a real-world problem with no single "correct" answer and that would require them to make assumptions and research new information not found in the text. A second objective was for students to apply the three major heat transfer mechanisms studied in the course: conduction, convection, and radiation. A third objective was to successfully work together in teams where success was defined as producing a design that met the given specifications and was completed by the assignment deadline.

Design Specifications

Design constraints are a necessary part of real projects. Schedule and budget are often two important constraints, but there are usually many more depending on the type of project. In this project, the budget was ignored but there was a deadline for the design to be completed which was the last day of class. Besides adding realism, constraints also limit the scope and help make assessments of multiple projects more consistent.

The immediate objective of the project was to design a 1 story 1500 ft^2 house in Tulsa, Oklahoma and then to determine the heating and cooling loads to size the heater and the air conditioner. In this problem, heat transfer through the foundation and roof were ignored and only heat transfer through the outside walls was considered. All penetrations through the exterior walls such as electrical outlets, gas and water pipes, cable lines, etc. were ignored. All overhangs (e.g., roof overhang, awnings, porches, etc.) were ignored in the solar radiation calculations. It was assumed there were no obstructions (e.g., trees, bushes, berms, garage, etc.) next to the house.

The walls had to include an outside layer of brick and an inside layer of drywall and could not be any thicker than one foot. The walls had to have studs on 16" centers and be 9' tall. The students had to select the components in the wall between the inner and outer layers, which had to be the same construction for all outside walls. The house had to have an outer wall facing each direction (N, S, E, and W) and all outer walls had to be straight.

There had to be two outside doors (1 in the front and 1 in the back) at least 36" wide that were commercially available and had some type of window in them. The outside windows had to also be commercially available and all rooms except bathrooms and the laundry room had to have at least one window of reasonable size (no port holes). The students had to select actual doors and windows and use the given manufacturers' insulation specifications.

The house had to have a family room, 3 bedrooms each with a closet, 2 full baths, a powder room, kitchen, and laundry room. The family room, bedrooms, and kitchen had to be at least 10' x 10'.

<u>Calculations</u>

Students had to determine the average conditions in Tulsa for each season (summer, fall, winter, and spring). This included wind speed and direction, solar radiation amount and sun angle, and ambient temperature.

The calculations had to include forced convection (wind) and solar radiation to the exterior wall (ignoring external natural convection), conduction through the wall, and natural convection and radiation to the interior wall. An important factor in the selection of this project was that it included all three major heat transfer mechanisms: conduction, convection, and radiation. It also included both major types of convection: forced and natural. It was designed to show students how multiple topics they studied during the semester could be applied to a single problem.

<u>Deliverables</u>

All drawings had to be computer-generated (e.g., CAD, PowerPoint, Excel, etc.). They included a plan view of the floor plan with North indicated, elevation views of all 4 exterior walls, and details of the wall construction. The wall details had to be shown in a typical cross-section through the wall. The manufacturer and model numbers for the windows and outside doors had to be given.

Heat transfer calculations (in English units) had to be provided for the average daily heating or cooling load for all 4 seasons. The house interior temperature was maintained at a constant 68°F. All equations, assumptions, properties, and sources used had to be clearly specified. Table 1 had to be completed for the calculated daily heating (positive values) or cooling (negative values) for each wall:

Table 1. Calculated daily heating (positive) and cooling (negative) loads by season.

	Spring	Summer	Fall	Winter
North wall				
East wall				
South wall				
West wall				
Totals				

Grading

Table 2 shows the rubric for this assignment which accounted for 10% of the overall course grade and how each team did for each component.

Table 2. Grading rubric and teams' performance.

Component	Rubric	Team 1	Team 2	Team 3	Team 4	Average
Meets all specifications	30	30	30	30	30	30.0
Window & door selections	10	10	10	10	10	10.0
Weather data for Tulsa	10	8	8	10	8	8.5
Drawing	5	4	5	5	5	4.8
Calculations	40	30	32	32	30	31.0
References	5	5	5	5	5	5.0
Total	100	87	90	92	88	89.3

Selected Results

Some selected project results are shown here for illustration purposes. Contrary to the assignment specifications, Figure 1 shows a hand-drawn rather than a computer-generated drawing of a final design. Figure 2 shows an example of a computer-generated drawing of a final design. Figure 3 shows an example of a 3-dimensional drawing of a final design.

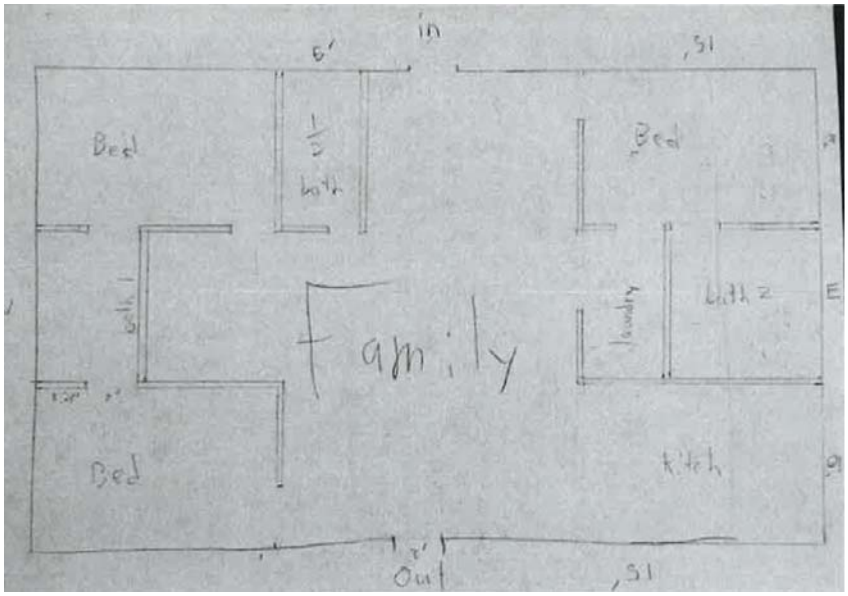

Figure 1. Example hand-drawn sketch of a final house design floor plan.

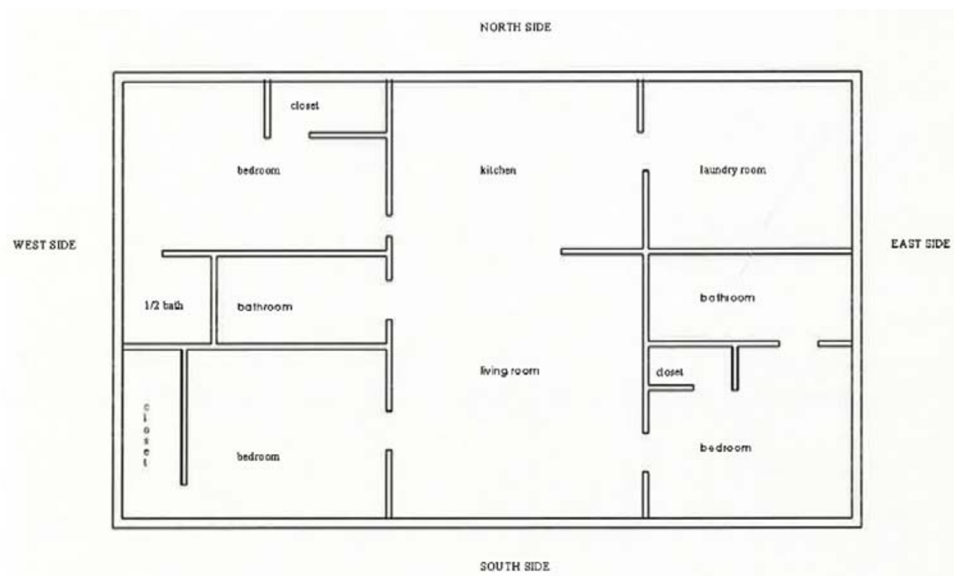

Figure 2. Example computer-drawn sketch of a final house design floor plan.

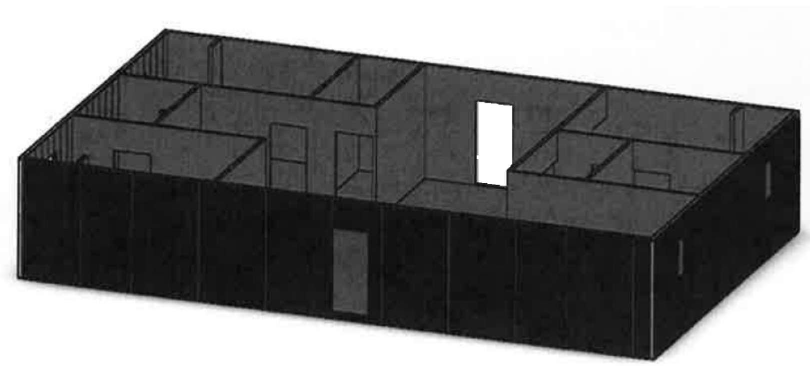

Figure 3. Example computer-drawn sketch of a final house design floor plan.

Figure 4 shows a hand-drawn cross-sectional view through the outside wall with an instructor's note that the team should have included plywood between the brick and the studs. Figure 5 shows an example of a computer-generated cross-sectional view through the outside wall.

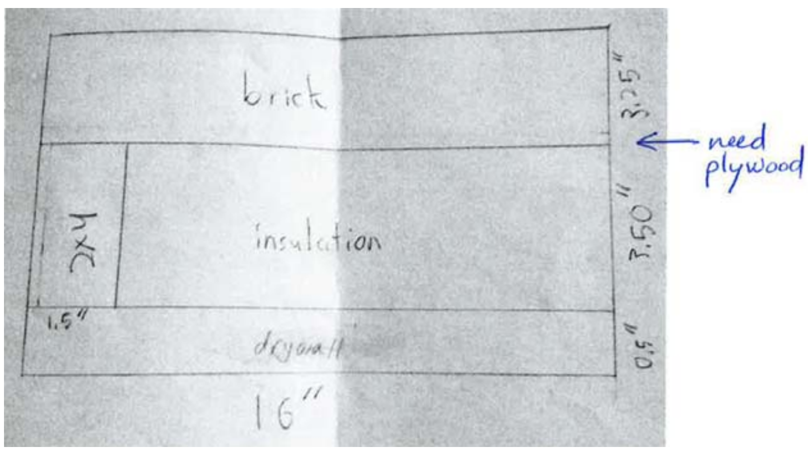

Figure 4. Example hand-drawn sketch of wall cross sectional detail with an instructor's notation.

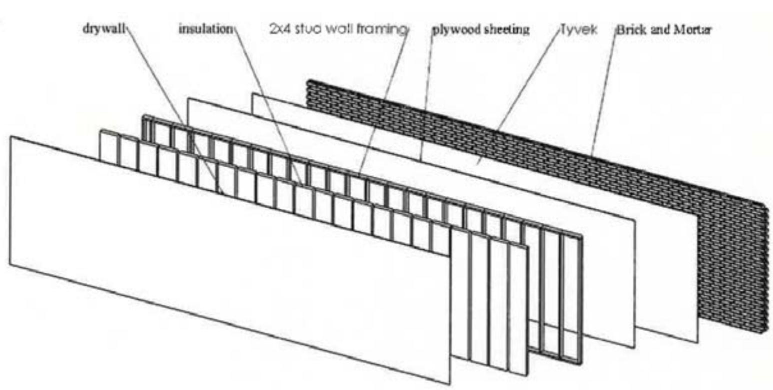

Figure 5. Example computer-drawn sketch of a wall cross sectional detail.

Table 3 shows an example of a team's weather data for Tulsa.

Table 3. Example weather data for Tulsa.

	Wind Speed (Mi/hr)	Solar Rad (BTU/h-ft^2)	Ambient Temp. (F)	Sun Ang (Deg)
Summer (6-8)	8.7	280	90	16.2
Fall (9-11)	8.87	203	75	45.3
Winter (12-2)	9.33	158	50	54
Spring (3-5)	10.6	258	70	25.5

Table 4 shows an example of one team's final calculations. They specified the wrong units which should have been Btu/h. Table 5 shows another set of final heat transfer calculations from another team where all of the values were negative which in this case indicates heating. Those results do not make physical sense where heating would be required even in the summer in Oklahoma. They show more heating is required in the spring than in the winter. There are also way too many significant digits. Both of those teams failed to critically assess their solutions (Baukal 2015).

Table 4. Example heat transfer calculations for daily heating (negative) and cooling (positive sign above values in winter) values (Btu/h-ft^2-°F).

Wall	Summer	Fall	Winter	Spring
North	9,600	2,970	-7,180	843
East	5,670	1,750	-4,230	496
South	9,600	2,970	-7,180	843
West	5,670	1,750	-4,230	496
Total	30,500	9,440	-22,800	2,680

Table 5. Example heat transfer calculations for daily heating (negative).

Season	Total Heat Transfer (Btu/hr)
Winter	-2253.93
Spring	-2417.62
Summer	-1371.61
Fall	-1308.11

Planned Modifications

A number of modifications are planned for this project which will be assigned again in the fall 2017 semester. The first planned modification is to better integrate the project with the course content. Students were encouraged to work on the project throughout the semester, but there was not enough emphasis on how a given topic would be used in the project. For example, after one-dimensional conduction was covered, there should have been a discussion of how that applies to the project where students should have been encouraged to start working on the conduction through the outside wall. While they in theory would not have been able to calculate that yet without knowing the convection and radiation boundary conditions which they would not have studied yet, they could have set up the conduction formulation while it was fresh on their minds.

Another modification for next time is to schedule time for the teams to present their designs. The first time the house project was assigned, the design was due the last day of class and no time was scheduled for the results to be presented. This was a missed opportunity to see how the teams approached the problem, how their designs were similar and different, along with a chance to get some feedback on the assignment itself. The assignment was also too late for students to receive feedback on the project as they only saw their final grades posted on the electronic course management system. The major reason for making the assignment deadline so late was that radiation was covered at the end of the course and was needed for design calculations. The assignment deadline will be made earlier in the course to allow students to receive more specific feedback. While some hints will be given next time for how to do the radiation calculations before radiation is covered in the course, this will also be a chance for more PbBL as students will have to do some advance research to make those calculations before the material has been fully covered.

Related to the previous modification, no specific format was given for how the teams would report their results. Three of the teams prepared a formal report while the fourth team, after requesting permission from the instructor, prepared a series of PowerPoint slides. Future assignments will require a presentation rather than a report for several reasons. This will make it easier to present the results to the entire class, it will reduce the burden of formally documenting the results, and it will provide the instructor with a convenient means for using some of the slides to discuss the project with future classes.

No formal survey was collected for the house design project. On a general survey question about what was the student's favorite part of the course, one student listed the house project. On another question about what was the student's least favorite part of the course, another student listed the house project. It is hoped the planned project modifications will at least remove the house project as a student's least favorite part of the course and make it the favorite part for more of the students. A formal survey with specific questions on the house design project will be given next time.

The grading rubric will be modified. As can be seen in Table 2, all of the teams' designs satisfied the design specifications including the window and door selections. The worth of this component will be reduced next time as it was easy enough to satisfy. The calculations component will be increased and broken into multiple sub-components such as conduction, convection, and radiation.

Some of the project specifications will be modified. Specific project objectives will include sizing and selecting a furnace and an air conditioner for the house (recognizing the heat transfer through the roof and floor have been neglected). Instead of the same ambient air temperature inside the house for all seasons, it will be assumed those temperatures will be 72°F, 70°F, 68°F, 70°F for the summer, fall, winter, and spring, respectively. Students will select the city where the house will be built. Rather than using the average conditions for each season, students will be asked to find the worst case so the heater and air conditioner can be sized to handle those conditions. A few more directions will be given for assumptions (e.g., assume solar radiation only hits the southern wall) to simplify the problem. Students will also be asked some specific questions that must be answered such as:

- Do the calculations over- or under-predict the real heating and cooling loads and why?
- Can any heat transfer effects (e.g., interior radiation or natural convection) be reasonably ignored?
- List at least 3 things that could be done to reduce the heating and cooling loads and discuss why.
- To minimize total energy requirements for heating and cooling, is it better to have a square or rectangular house and if the latter, which directions should the long sides face?

Options

There are numerous options for modifying the project described here. A few will be discussed here as examples. One possible modification is to provide a house that has already been designed and have students analyze it to determine the heating and cooling requirements. This could be a house designed on paper but not actually built or it could be an actual house. This would significantly reduce the scope and the amount of time the project would take. A variant of that is to take an existing design and have students improve it with some constraints such as the extent of permitted modifications or the types of changes that can be made.

There are many possibilities for the effects of the time of the year. The scope could be limited to looking at the heating/cooling for a single day, week, month, or season. Different groups could be assigned different times to consider. Actual data (e.g., ambient air temperature, wind speed, solar radiation, etc.) might be recorded for a particular day that could be used in the analysis.

Another option would be to have students determine costs. This could be limited to just the heating and cooling systems or it could be expanded to include windows, doors, and even the wall construction. These would expand the scope but could be considered if the teams are large enough.

Conclusions

This paper describes a comprehensive semester-long ill-structured project to design a house according to certain specifications and then to analyze that design using heat transfer principles learned throughout the course. The only other related project found in the literature was a house design project that was part of a Department of Energy Solar Decathlon to incorporate passive solar principles (Marshall et al. 2002). However, this was for a competition rather than an assignment in a course. The primary purpose of a summative project is to have students demonstrate they can apply the principles learned in class to an actual problem. As some of the results demonstrated, students calculated heat transfer rates that did not make physical sense (e.g., heating required in all 4 seasons and more heating needed in the spring than in the winter). While many changes will be implemented the next time this project is assigned, it did demonstrate this can be an effective and challenging method for students to apply a wide range of theory learned in a particular course to an actual problem (house design).

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