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Project-Based Curriculum for Thermal Science Courses

Abstract

The incorporation of semester-long projects into two different courses are discussed in this paper, one project in a senior-level Fluid/Thermal Design course (F/TD) in the Engineering curriculum and two projects in a junior- or senior-level Thermodynamics and Heat Transfer course (T-HX) for the Industrial Supervision/Advanced Manufacturing curriculum. The content of both of these courses has been delivered as a project-based learning (PBL) experience. In each case, the project has involved HVAC system design and building energy analysis: a renovation analysis for a house in a low-income neighborhood, identifying upgrade and retrofit options for an architectural award-winning building, and an analysis of a new construction building on campus.

Around this building analysis project framework, the entire content of the course has been structured, and has included: HVAC system design and components including sustainability and efficiency concerns, building envelope U-values, load calculations, psychrometry, instrumentation, design considerations and strategies, alternative energy and geothermal system options, finite difference computational techniques, computational system modeling with Newton-Raphson solution methods, and use of a commercially available building software model to simulate possible retrofit modifications and match measured loads. The classes have participated in field trips to the respective buildings to make measurements of room dimensions, air flow rates, temperatures, and relative humidity throughout the building and to clarify points of uncertainty from reading the blueprints.

By providing the students with the theoretical material that was immediately relevant to the project at hand in the lecture lab sessions, the conceptual understanding was aided by direct application. In addition, the projects demonstrate the relevance of the material from their thermodynamics, fluid mechanics and heat transfer classes in a tangible way. The student interest in the material was observed to be increased as judged by the level of engagement during and after class time.

This paper describes the structure of the courses between the lecture material and the project and how the learning outcomes for the course are approached. In addition, the practical considerations that have arisen through the semesters with regard to real world engineering design issues are discussed. Finally, observations of student learning is presented and discussed to gage the advantages of using a project-based curriculum.

Introduction

Project Based Learning

Engineering education traditionally consists of lecture-based instruction, which is indisputably the most efficient method for *communicating* large amounts of information quickly. However, as engineering faculty are looking for innovative ways to *teach* information, the standard lecture-based classroom is being augmented by additional or alternate instructional techniques. One of these techniques is project based learning, wherein the course material is delivered through class projects, usually organized in a group setting. There are many instances of project based learning (PBL) found throughout the Engineering educational literature.

Project based learning (PBL) is one type of student-centered learning, where the teaching methods produce an environment of active learning rather than passive. This encourages creativity as the curiosity within each student motivates the learning process. By allowing the learning to happen within the context of a project, the efforts of the students are all directed towards a end goal. In a published meta-analysis of 43 different project-based learning studies[1] it was shown that overall, students taught with PBL techniques were able to demonstrate a significantly longer retention period for the acquired knowledge, as well as a significantly positive effect on the skills they learned, with no negative effect reported in any of the studies. The only negative tendency that could be discerned, which was small enough to be almost insignificant, was that the amount of knowledge gained in a PBL class. So, giving the worst interpretation of these study results, PBL students learn more skills, slightly less knowledge, and retain more of the knowledge two years later when compared to non-PBL students.

Using a PBL approach has the advantage over the more traditional case study because while the use of case studies adds realism and improves student engagement, there has not been shown any significant difference in the conceptual understanding of the students by the use of case studies[2].

Several instances of thermal sciences classes implementing a PBL approach can be found in the literature as well. PBL techniques have been incorporated into a thermal science laboratory class by using inquiry-based initial techniques, followed by PBL application in virtual LabVIEW laboratory exercises that were developed to be open-ended specifically for this purpose[3]. By implementing the material in this way, the students were given more responsibility in conducting the experiments and given a better understanding of the inner workings of the data acquisition systems. This was claimed to have significantly improved the quality of the laboratory education.

In an undergraduate heat transfer class, team-oriented PBL techniques were used to teach the material[4]. This course also used simulations for the various projects involving numerical techniques within the projects to model the various heat transfer modes. The projects were done in groups, and this paper discusses why a shift to structuring the educational process around tools (such as Excel spreadsheets) that will be available to practicing engineers is a good thing. This included instances of student feedback that they were able to implement techniques learned in that class in their summer internships.

Two other Thermal Fluids laboratories have incorporated PBL in a design-build-test framework[5,6]. One class[5] allowed the teams of students to pick between seven different options of fluid thermal test equipment, ranging from natural convection equipment to open channel flow, and construct an experimental apparatus. These students demonstrated successful completion of an open-ended design problem, which included dealing with tradeoffs of resource constraints of time and money. The other class[6] specified that the student teams construct a heat exchanger given design conditions. This resulted in a wide variety of designs, and a wide variety of success for those designs, and also included budget analysis. The students were observed to have enjoyed the class, and the assessment found the experience to be successful.

Another PBL project in an electrical engineering program, but based on a heat transfer project, was performed with regard to a heat sink on a computer chip[7]. The students involved in this project were first year graduate students in the electrical engineering program, and analytical methods were used for the solutions to the heat diffusion equation. It was observed that students used a wide variety of sources to complete the project, including engineering handbooks, textbooks, lecture notes and internet sources. The appeal to a wide variety of sources instead of having a single assigned textbook is the method that was used in the present study.

Common to all of these successful examples of PBL implementation is that the instructor has developed the projects for the purpose of using them in the educational process.

The Present Study

This present study discusses the project-based curriculum that was used in two different thermal science courses, *ENGR 465*: *Fluid/Thermal Design* (*F/TD*) which is part of the Engineering program, and *TECH 351*: *Thermodynamics and Heat Transfer* (*T-HX*) which is part of the Industrial Supervision and Advanced Manufacturing programs. Two different building study projects have been run in subsequent semesters of the *T-HX* course: the Washington Avenue house and the Business and Engineering Center; and one project in the *F/TD* class: the Atheneum building.

In the Department of Engineering at this University, there are three separate degree programs offered: Engineering (BSE), Industrial Supervision (IS), and Advanced Manufacturing (AM). *F/TD* is a design course in the Mechanical Engineering emphasis of the BSE program. It is taken as an elective by graduating seniors who have completed Thermodynamics, Fluid Mechanics and Heat Transfer. The IS curriculum combines business courses such as organization and management and cost accounting, technical academic courses such as CAD drafting and quality control statistics, and hands-on manufacturing courses such as CNC mill operation and robotics. The AM program does not contain the business component of the Industrial Supervision degree but includes to the curriculum technical courses such as a non-calculus-based statics, material science, work cell and production systems design. The course *T-HX* is taught to juniors or seniors in the IS and AM tracks, and is their first exposure to the thermal sciences. Both the *F/TD* and *T-HX* courses consist of two hours of lecture and three hours of lab each week, for three hours of credit.

For the last three semesters, the instructional material in these two courses has been structured around a single project shared by the entire class. The projects have all involved building energy analysis, including the basics such as heat conduction through the building envelope and psychrometry, but also more practically-oriented topics such as building load estimation and sizing of the HVAC system to the buildings. The project provided a framework to the lecture material wherein the lecture material was all related to topics needed for the project. Each semester the class has visited the building that is being studied which provided a physical frame of reference to the project and a hands-on element to the lecture material. The student engagement was observed to be higher than in these classes that in classes that have a purely academic focus.

For two of the projects, the Washington Ave House and the Atheneum, there was a significant external component to the work in that the class made a final report to someone other than just the instructor. This is different than the typical instance of a PBL class in that the instructor usually develops the project for the students. As discussed later in this paper, the instances that the class discovered something that the instructor had not expected were some of the times that the class engagement was the highest. This format puts the projects closer to the realm of a project-based service learning, which has been shown to increase retention, and enhances student preparation for engineering design work[8]. The external component of the projects discussed here could almost be considered to be a case study of the different buildings, except that the traditional engineering case study is usually a study of catastrophic failure. By studying non-catastrophic cases, the students were exposed to the regular aspects of engineering analysis, in an open-ended manner.

Unfortunately, it had not been anticipated that detailed assessment data would be desired from these classes, and so none of the students were asked to sign a study agreement to be filed with the University's Institutional Review Board. This is an unfortunate oversight that precludes the inclusion of any grades or other quantitative assessment data in this report.

Layouts of the Courses

No Assigned Textbooks

Since the courses were structured to use the project to deliver the learning experiences, there were no assigned textbooks for the class in any of the semesters. Handbooks from the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) were available to the students for use. These reference books were used to look up the values of thermal resistance for the various building materials, as well as for the descriptions of the various procedures for hand load calculation, resistance networks. These values and methods were needed in both the computer and hand calculations of the building loads.

The purpose to running the classes without textbooks was to familiarize the students with the multiple real-world references that would be needed in their engineering careers. The lack of an assigned textbook was not seen to be a hinder on the student ability to use the references provided. At the end of each semester the University administers evaluations, and one of the questions on this evaluation is: "The course materials used, such as visuals, texts, handouts and on-line items, helped me learn." The students respond on a scale of 5 to 1 with 5 being "Significantly Agree" and 1 being "Significantly Disagree." In all of these semesters, the average for this question is in the high 4's, and none of the students have ever selected lower then 4 ("Agree") on this question, indicating that the students did not find the use of reference material to be a detriment.

Content of Lectures

The exact timing and content of the semesters varied widely between each of the three semesters and from course to course. The *F/TD* class, since the students had been exposed to the thermal fluids curriculum, was able to start into applied material early in the semester. The *T-HX* class, being the first formal introduction to the topics needed to start at more of the introductory material for a longer period of time. The first laboratory exercise of the *T-HX* class was a "BTU Lab", which covered the basics of heat capacity and energy transfer by boiling water, melting ice and heating water with a candle, and observing the specific heat and latent heat from the temperature vs. time curves. A refrigeration systems lab was used in a later lab exercise, using refrigerant trainers.

The overall intent of the lectures was to frame the topics of the course as applied to the project, and the earliest lectures were used to introduce the students to the project and to the basics needed for the project. Lecture time later in the semester was sometimes used by the students to make formal presentations to one another on the project work. With the different groups of students working on different topics of the project, this was an essential part of keeping everyone informed about the material and progress being made. Lab time was sometimes used in the computer lab to develop the building model; either using the software packages or in the hand models. Sometimes, later in the semester, questions arose in the course of the projects, and lectures were prepared for the next class period with material the students could use to resolve those questions. The building blueprints were extensively used in the lab time, and several lab periods involved pinning up the various blueprints all around the room as students referred back and forth to them to develop the computer models.

With regard to the effectiveness of this manner of instruction, one of the questions asked in the end of the semester student evaluation forms was "The instructor's teaching style was effective for me." Again, the student responses averaged to the mid-4's ("Agree"), only one student marked a 3 ("Neither Agree nor Disagree"), and no students marked "Disagree" or "Strongly Disagree". Since the "teaching style" can be understood as the manner of instruction for this class, this is an indication that no students found the project-based methods to be ineffective.

Techniques of Assessment

In the *T-HX* class, the students were given traditional methods of assessment: tests, quizzes, and a final exam. In addition, they were required to maintain and turn in a project field manual in which they logged the work they did on the project. A final oral report was required for the project work, in which all of the students presented a part of the project that they had contributed to. The students were able to demonstrate their understanding of course objectives by their performance on these methods of assessment. Since the *T-HX* class is not part of the ABET accredited engineering curriculum, no formal learning outcomes were indexed for the class.

In the *F/TD* course, the ABET learning outcomes were presented to the students on the initial syllabus as:

> 1. The ability to design and conduct experiments, as well as analyze and interpret data (ABET outcome b). In particular, you will be expected to:

i. Interpret power usage and energy consumption data for the Atheneum building.
ii. Design and execute and necessary experiments to confirm or verify analytical findings related to the building analysis.

2. The 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 (ABET outcome c).
i. Design and analyze alternate cooling systems for the Atheneum building.
ii. Conduct economic analyses of the various systems proposed.

3. The ability to identify, formulate, and solve engineering problems (ABET outcome e). In particular, you will be expected to:
i. Solve heat loss problems relating to building envelopes.
ii. Solve problems of thermodynamic equilibrium and energy balance.
iii. Solve piping and airflow distribution problems.

4. The ability to communicate effectively (ABET outcome g). In particular, you will:
i. Write technical reports and memos regarding findings.
ii. Make presentations of technical material to peers and colleagues.

5. The ability to use the techniques, skills, and modern engineering tools necessary for engineering practice (ABET outcome k). In particular, you will be expected to:
i. Conduct a building simulation using TRACE building software.
ii. Use EES software to solve systems of thermodynamic equations.

As evident from the expectations listed for each outcome, most of the outcomes were demonstrated by means other than traditional assessment methods. No exams were given in this class. Instead, the students were required to present the work they had been doing to one another, write short reports on different sections of the project, and perform various aspects of the analysis as homework assignments. With only nine students in the class it was not difficult to make sure that everyone had contributed something for the assignments that were group work.

Descriptions of the Three Projects

Washington Avenue House

The Washington Avenue house project was the first of these projects to be run, and was incorporated into the *T-HX* course in the fall semester of 2008. Developed in conjunction with the Service Learning Institute on campus, the purpose of the project was to address energy savings in an older construction house located in a low-income neighborhood. Service Learning is a community-based pedagogy technique which integrates meaningful community service with instruction. The Washington Avenue house was an abandoned (possibly due to a bank foreclosure), 1,950 square foot, two story residential house with no insulation in the exterior walls and single-pane windows. A photograph of the front of the house is shown in Figure 1. The intent of the project was to explore a variety of different possibilities for improving the energy efficiency of such a house, since that construction is typical of the neighborhood where it is located.

Figure 1: Washington Ave. House

No blueprints of the house were available to the class, so a field trip of the class to the site was needed to supply the dimensions needed for the analysis as well as to confirm the construction of the walls.

Building loads were calculated both by constructing a model of the house in the Trane Trace 700 program and by hand calculations using the cooling load temperature difference (CLTD) method for the walls and roof and glass load factor (GLF) method for windows. The effects of adding insulation, installing more energy efficient windows and other envelope improvements were investigated by the students, and presented in the context of a payback period for the added cost.

High efficiency and alternative energy heating and cooling systems were explored by the students. This required the students to research what was available in order to determine the different options, such as a condensing furnace, geothermal heat pump, solar hot water panels, photo voltaic (PV), and fuels cells. Then these were analyzed using Trace 700 for their economic viability.

At the conclusion of the project, the class made a combined presentation of all their findings to representatives from the local Habitat for Humanity and also the local electric and gas utility.

Atheneum

The Atheneum building project was run in the *F/TD* class in the spring semester of 2009. The Atheneum building is an award-winning architectural design and is used as the visitor’s center of Historic New Harmony, which is restoration project maintained by the University. Unfortunately, the architectural award was for its appearance, not the thermal efficiency of the building, and the amount of energy required to heat and cool the building is quite high. A photograph of the building’s southern exposure is shown in Figure 2, where the high percentage of single-pane glass indicates the high solar cooling load from the summer time and the high conduction heat loss in the winter time. The utility bills over the past few years have been growing, and the director of Historic New Harmony approached the Engineering Department about doing a feasibility study for the installation of a geothermal heat pump. Coming out of this discussion, it was decided to use the building to perform an energy analysis of the entire building with the *F/TD* class and evaluate the economic possibility of a geothermal installation as a senior capstone design project. The seniors working on the geothermal heat pump for their senior project were also part of the class which allowed them to use the results from the class work to support their project. For example, the computer model that the class developed was used to verify the required capacity for the building. During one lecture period, the senior design team gave a presentation to the rest of the class on the various styles and types of geothermal heat pumps that are commercially available for this size of a building.

Figure 2: Photograph of Atheneum building showing southern exposure

The first stage of the energy analysis was to compare the past year of gas and electrical usage to the weather data of the same time periods as the bills. This involved collecting historic weather data from a website and comparing the heating- and cooling-degree days to determine average values for the insulation abilities of the building. The degree-day bin method was presented in lecture and the utility data were distributed to everyone in a spreadsheet, and the homework assignment was made to collect the weather data and complete the insulation value for the building. However, it was discovered by some of the students that the data available online was in error for a few days during one of the periods. During a lab period, the whole class together decided what to do with the incorrect data. A spreadsheet of the utility data was displayed on the classroom projector and the sums for each billing period were calculated on the chalkboards, and the modifications made by the group were used in the final analysis.

For the next stage of the energy analysis, the blueprints of the building were used to develop a computer model of the building for analysis of the heating and cooling losses. Each of the three floors was assigned to a different team of students who were responsible for developing a model for the rooms on that floor. The program Trace 700 was used in this class to calculate building loads and energy analysis. In the Atheneum there is a lot of open atrium space with mezzaninelike rooms on the second floor that connected through to the first floor. This unique floor plan made the modeling process more complex than for a standard building. In addition, the organic shapes of the walls and windows were not always well suited to the inputs required by the program. Little or no guidance was provided by the instructor of the class with regard to any required way of modeling the space, and the students were given the freedom to represent the wall area and glass exposure and tilt direction. The students performed this task well.

When the development of the building model was underway, but before it was complete, the class made a field trip to the Atheneum building. One of the reasons for this trip was to answer any of the questions that had arisen from the initial analysis of the blueprints. Since there were several unique design structures, the students did not always find it straightforward to understand the blueprints with regard to the multiple levels of some of the atrium floors. Another reason for the visit was to take temperature and air flow measurements of the rooms in the building. Air flow meters, infrared thermometers and a sling psychrometer were brought along for this purpose. The students were given the run of the building, including the mechanical room and the rooftop which houses the condensing units and air handlers, and during the trip, the final decisions were made with regard to the partitioning of the building space within the computer model.

The completed building model was used to determine the relative importance of the different components of the utility costs. As expected, the solar load through the windows and skylights were the significant contribution to the summer time cooling load, but the high percentage that these (single-pane) windows contributed to the winter time heating load was a surprise. Various ideas to reduce the solar load were brainstormed by the class, and the viabilities of some of them were investigated.

Finally, opportunities for alternative energy production were investigated by the class, including PV, solar thermal, and wind installations and even an investigation into small-scale hydropower installations that could be made on the river. None of these proved to be feasible but the investigation required the students to make an extensive survey of the available methods of alternative energy production and their advantages.

At the conclusion of this project, a report was submitted to the Director of the Physical Plant of the University and the Director of Historic New Harmony with the class findings and recommendations.

Business and Engineering Center

The Business and Engineering Center is a building currently under construction on the university campus that will contain – as the name implies – the College of Business and the Department of Engineering. This $34 million building has four stories, enclosing 120,000 square feet of lab, classroom, and office space. This building was chosen for the fall 2009 semester project of the *T-HX* course. The location of the Business and Engineering center is immediately adjacent to the building where the Engineering Department is currently located, and the construction is obvious to everyone in the building. Since the blueprints were available and the students take a personal interest in the building, it was chosen for the most recent class project.

Figure 3: Photo from Construction-Cam of the Business and Engineering Building

The fact that the building to be studied was still under construction meant that there was no existing energy usage data to examine. However, it also meant that the class could see the exposed ductwork and heating lines. Several field trips were taken throughout the course of the semester so that the building could be seen in various states of completion.

Since no external requirements were in place for this project, the same general procedure was followed for the project of performing the building load analysis in order to develop the required size of the air handling unit. Because of the complexity and size of the overall building, only one room was selected to compare the hand calculated load to the computer model load. A north-east facing room with significant window area was used for this comparison. This was a fortuitous choice because an unexpected difference was discovered between the cooling loads calculated by hand and by the computer model. For the hand calculations, the peak cooling is always assumed to be in July at 4 pm and the calculations are based on this assumption. In the computer model, the solar and sensible cooling loads are calculated from hourly weather data. For this room, the peak load was actually determined to occur in October at 10 am because of the eastern exposure. The exercise of the students reconciling this difference between the two calculation methods was a significant one, and an observation about the competitive nature of the students is discussed in the following section.

Observations of Student Learning

Throughout the semester, a variety of observations were made with regard to student learning. Some of these observations were expected, but some were surprising and are considered unique to the project environment. One of the unexpected observations was the increased student interest when the class discovered something that the faculty member did not expect. In the case that was already mentioned of the peak loading difference between the hand and computer calculation of the Business and Engineering Center, and again when the computer load of the Atheneum did not match to the electrical bills, the students seemed to be trying to race the faculty to determine the correct answer. In the case of the Atheneum discrepancy, it was the outside air load that was found to account for the difference, which was discovered after significant effort was put forth by the students and a number of other (smaller) errors were corrected.

If this can be attributed to a competitive spirit towards the faculty by the students, this same competitive spirit was also observed was between students which also led to learning. At one point, some of the building calculations were assigned to be completed as homework and were turned in. Upon seeing the submitted work, the faculty noticed that there was a lot of difference between the various numbers, which should have been identical. It was announced that everyone should put their calculation in a common spreadsheet displayed on the classroom projector in order to reconcile the numbers. None of the students were willing to put their calculations up for display until they had checked through them again, even though just minutes earlier they had been willing to turn them in for a homework grade. Eventually all the errors were found and a consensus was reached. It was evident that the additional social pressure of sharing their work with their peers made the students motivated to take more care with their calculations that if they were just handing them in to the teacher.

One of the observations of student learning was the additional engagement and ownership that the students took of the project during lab time. The lab time ended for both classes at 5 pm, and it is common to observe students who want to wrap up early. While working on the projects, however it was not uncommon in lab sessions for the students to be engaged with the project up until and even sometime running over the allotted lab time. It is believed that the reason for this is when the lab time was used for the project the students were participating in creative work: identifying new problems and creating solutions. This is a more engaging activity than the traditional labs which have students going through pre-defined procedures. During the field trips to the respective buildings, the students were all thoroughly engaged in the project at hand and in each case the field trips took more than the scheduled lab time without any complaint from the students. At the field trip to the Atheneum, the students started trying to measure the heat given off by a single radiator unit by trying to perform an energy balance on the temperature of the inlet and outlet pipes for the hot water. While this did not result in useful data, it was evidence of active participation in the task at hand because that idea for such an energy balance was entirely initiated by the students. Also for the Atheneum project, one of the groups performed a finite-difference heat transfer analysis of the ground loop that would be needed for installation of a geothermal cooling loop, again on their own initiation.

One final observation that was completely unexpected was made during the Washington Avenue house field trip. Upon initial arrival to the site the students appeared uncomfortable even made some comments about the "rough" neighborhood the house was located in. However, throughout the course of the visit, and even more through the course of the rest of the project, the students were observed to take ownership in the house and in the plight of the houses in that neighborhood with respect to the energy efficiency. No formal opinions were solicited from the students, but the informal observation of the instructor was that this group of students seemed to have broken through a small element of prejudice towards the neighborhood as a result of the project.

The student feedback on the end of the semester evaluation has consistently been favorable, with everyone in all the classes except for one student agreeing or strongly agreeing that "the teaching style was effective for me" and that they "learned a lot in this course" and every student every semester either agreed or strongly agreed that "the assignments helped me increase my understanding of the course content."

Conclusions

Two courses in the thermal sciences have been taught for the past two years in a project-based format. One course is within the Engineering curriculum, and one is within the Industrial Supervision and Advanced Manufacturing curriculum, but both sets of students have been observed to benefit highly from the hands-on and focused activity. The course material was structured around the building energy projects and was provided in the format of regular lectures. Student engagement was observed to be much higher when the project was included, and several anecdotal instances were discussed to demonstrate the levels of engagement. Learning occurred when the problem or task presented itself, not as dictated by the syllabus. This type of learning is fast paced and effective. The students respond to tasks because they could relate to them and were motivated meet the end of semester deadline.

By applying the course material to the project, the learning occurred in a manner similar to engineering practice. Students are given an experience for their careers in the real world. The inclusion of quantitative assessment data, which was precluded because IRB approval had not been originally sought for these classes, would provide more context for the areas in which this teaching method could be better situated to the students' needs and learning styles.

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