Implementation of a Design Spine for a Mechanical Engineering Curriculum

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Implementation of a Design Spine for a Mechanical Engineering Curriculum

Abstract

This paper explains the approach taken to develop a "design spine" within our mechanical engineering curriculum. Developing a design spine started as a discussion about the ASME Vision 2030 document, which encourages programs to provide design experience throughout all four years of the curriculum. Towards this end, the mechanical engineering faculty reviewed our curriculum and identified where and how we do teach engineering design in lecture courses, laboratories, and in the capstone design courses. We recognized that many design elements are already incorporated throughout the curriculum but we needed to approach design in a more systematic manner. The very meaning of "engineering design" does not enjoy universal definition. For our purposes, we used the ABET Criterion 5 definition and original ABET 2000 requirements.

After the design spine was defined by the faculty, a survey of senior students was administered to evaluate the effectiveness of the design spine. Student survey responses are analyzed and a map for developing a design spine at other universities is provided.

Introduction

Design is inherent in engineering, yet it can be difficult to precisely define or describe what "engineering design" actually is. It is a process involving many steps, and typically involves teams of engineers and non-engineers. ABET in Criterion 5 (Curriculum) defines engineering design as follows:

> *Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.*

The distinguishing feature of many professional engineers is the way they think about the design process. Engineering educators have considered the best ways to teach design for many years to refine the education process. Problem Based Learning (PBL) is often considered one of the best methods for exposing students to the design process [1].

Dym et al. provide assessment data on the use of PBL in introductory classes and also in a global context [2]. Others evaluated PBL in the comparison of engineering and other education fields [3]. Orhun and Orhun encourage incorporating creative elements into the engineering education process to enhance problem solving skills in students [4]. The work of prior education research supports the inclusion of PBL whenever it might enhance the traditional engineering classes.

The senior level capstone course has evolved as a standard method for engineering programs to expose students to the creative design process near the end of education. Many authors provide a detailed review of engineering education capstone classes and benefits [5-7]. The practice of a creative and open-ended capstone course is widely believed to offer significant benefits to the students in professional development and engineering thinking. Our curriculum includes a standard two-semester capstone course for seniors in the program to experience design.

In our program we considered methods for better-preparing the engineering students for the design process prior to the capstone course. Leaders in engineering education have argued that the engineering curriculum should be evolving to allow more creative and open-ended elements through the full curriculum [8-11]. Other programs have addressed this idea using integrated design spaces [12] and Design-Build-Test (DBT) problems in the curriculum [13-15]. The "design spine" discussed in this paper builds on these works to document and assess how we have integrated design in all four years of a traditional mechanical engineering program.

Overview of the Design Process

Engineering projects may be broken into several distinct phases, although in reality, the phases overlap or may be even be entirely different from that presented here. Design is *rarely* a linear process, it is iterative in nature. Each design project is unique, there is no one process to follow for design. In general, the design process can be described as:

- Define the problem (which includes establishing objectives and criteria, and developing a plan),
- synthesize math, science and engineering knowledge to develop alternatives,
- evaluate the alternatives (through testing, analysis, literature search, etc.) and synthesize knowledge to select the best alternative.
- define and refine the details.

Through testing and analysis, detailed design work progresses from the design concepts. This process starts with conceptual design and commences to ever-more refined details until the finished product or design has been completed. Figure 1 summarizes the design process using a flow diagram.

ASME Vision 2030 for Mechanical Engineering Education [16] encourages mechanical engineering programs to have a "design spine" or "design portfolio" in their curriculum where students experience design throughout all four years. In 2012 the University of Portland mechanical engineering faculty reviewed the curriculum and identified where and how engineering design was being taught. Through this process we came to recognize that we indeed already have design elements throughout the curriculum. Our "design spine" has evolved over many years, and before making significant changes we recognized the need to assess how effective it is, pedagogically. Towards that end, by surveying seniors we collected data to indicate how effective the current curriculum is at helping students learn each step of the design process.

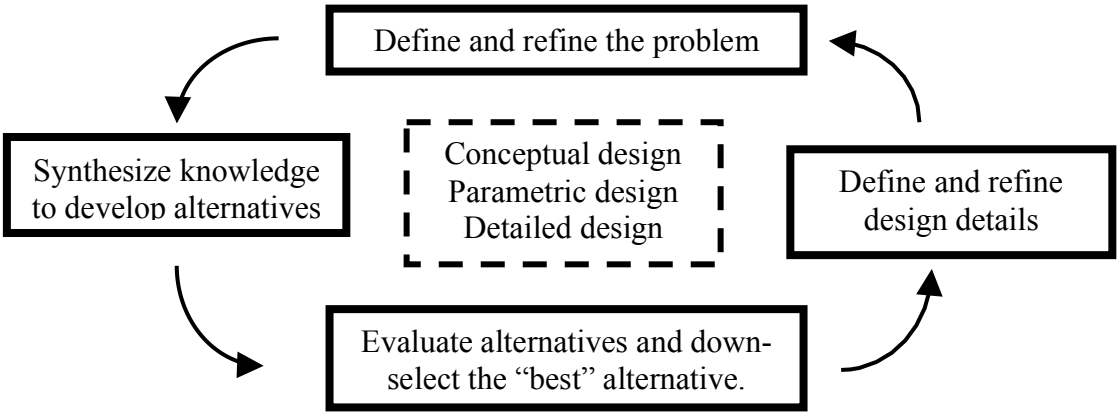

Figure 1 – flow diagram of the design process

Thirteen classes were identified by program faculty as relevant regarding pedagogy of various elements of the design process (Table 1). Faculty identified seven of the thirteen classes as "focus" courses. These "design focus" courses span the four years of the curriculum and include both thermal and mechanical systems. Each of the focus classes has a significant design project. In the first semester, students are introduced to the design process through an open-ended project in the *Introduction to Engineering* course. During the sophomore and junior years, the curriculum develops specific skills (such as setting design goals and objectives, using analysis and testing in open-ended problems) as well as helping students understand the design process as a whole. In the final year, students are involved with a year-long culminating design project of their choosing. This incorporates all that they have learned about engineering design.

This paper discusses the seven focus classes identified in Table 1. We will briefly explain the context of each of these courses and the elements of design in which they help students develop skills. We will then discuss two forms of assessment for each of these courses: instructor's assessment and results of a student survey. This paper will not discuss the senior capstone design course (which involves a two semester long project).

Table 1 – Mapping of courses to the fundamental elements of the design process.

Year:	1	2	2	2	2	3	3	3	3	3	3	4	4
	Intro to Engineering*	Dynamics	Materials Lab*	Strength of Mat'ls	Engineering Graphics	Finite Element Anal.	Mech. Systems Lab*	Fluid Mechanics*	Thermodynamics	Heat Transfer*	Machine Design*	Thermo Lab*	Capstone Design
Define and Refine the Problem													
Gather information, identify and understand the needs of the real problem	x		x	x		x	x		x		x		X
Set goals, objectives, define criteria for the solution to the problem	x		x	X	X		X				X		X
Establish criteria that includes multiple realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.											x		X
Develop a plan to solve the problem		x	X							x	X	x	X
Synthesize Knowledge to Develop Alternatives													
Generate ideas and concepts (brainstorm, etc.)	x	X		X	x		X	X	X	X	x	X	X
Evaluate Alternatives													
Evaluate through literature search			X										X
Evaluate through analysis	x			X		X		x		X	X	X	X
Evaluate through testing							X	X	X	x	X	X	X
Synthesize knowledge to down select to best alternative	x				x			x		X	X	X	X
Define and Refine Design Details													
Evaluate details to make sure the alternative is acceptable	x			X	x	X				x	x		X

Lower case "x" indicates minor coverage, upper case "X" indicates more extensive coverage.
The asterisk (*) indicates courses discussed in this paper.

Survey Assessment

To assess how student's perceived the design spine project outcomes in each course a survey was administered to senior level students in the Fall of 2014. The survey asked the students to rank how effectively each class project helped them learn each aspect of the design process. An example question from the survey is shown below.

The primary design project in *EGR110 Introduction to Engineering* helped me learn to:

	Strongly Agree				Strongly Disagree
Define and refine the problem	5	4	3	2	1
Synthesize knowledge to develop alternatives	5	4	3	2	1
Evaluate the alternative and down-select to the "best" alternative	5	4	3	2	1
Define and refine design details	5	4	3	2	1

The survey was completed by 37 students in the senior class representing most of the possible 45 students in the class. The student responses indicated that nearly all the projects offered some assistance in the design process, however some of the projects were perceived as more beneficial than others.

The full survey results were analyzed and the results for each part of the design process are shown in Table 2. Overall the design projects were ranked as most successful at helping students learn to define the problem and refine the design. The projects were slightly less helpful for the students at synthesizing knowledge in the design process and down-selecting alternatives. Since students learn to "evaluate" and to some extent "synthesize knowledge" through conventional closed-form assignments used in the preponderance of courses, it is less critical for the design projects to focus on these aspects. Design projects have the unique opportunity to help students learn to define problems and to refine the design details so those should be their focus. It is good to see that the projects are viewed as particularly beneficial in those respects.

Table 2. Summary of survey results by stage of the design process.

	Average Response	Distribution Details
Define and refine the problem	3.95	Figure 1
Synthesize knowledge to develop alternatives	3.79	Figure 2
Evaluate the alternative and down-select to the "best" alternative	3.73	Figure 3
Define and refine design details	3.87	Figure 4

Figures 1 through 4 show student responses for each of the four primary design elements. Data for each class are combined to show the design spine results, comprehensively.

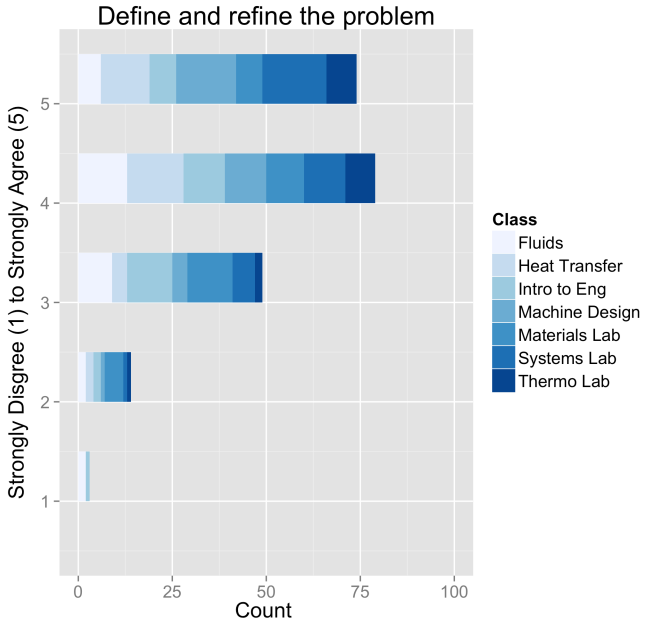

Figure 1. Student survey responses for defining the problem indicating the majority of students "agreed" or "strongly agreed" that they learned to "define the problem" through the design spine projects.

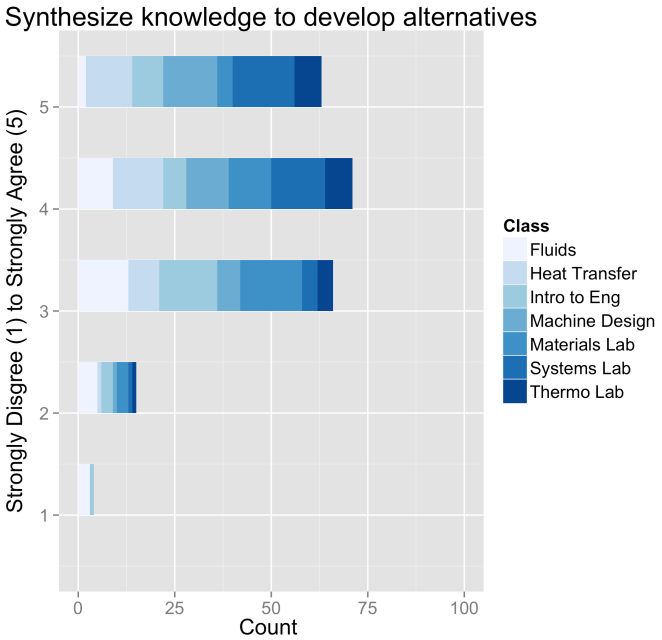

Figure 2. Student survey responses for synthesizing knowledge to develop design alternatives. The great majority of students generally expressed a neutral to "strongly" agree response for overall effectiveness of the design spine with regards to "synthesizing knowledge."

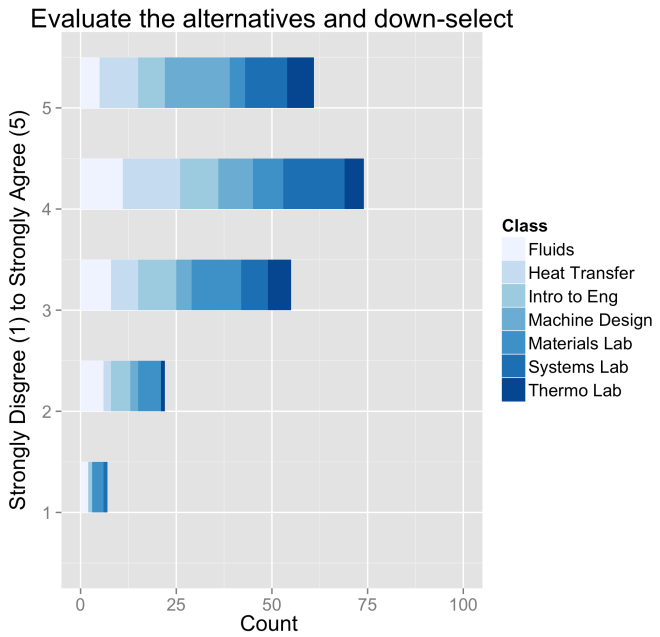

Figure 3. Student survey responses for evaluating alternatives and down-selecting the design. Most students generally expressed a neutral to "strongly" agree response for overall effectiveness of the design spine with regards to "evaluating alternatives."

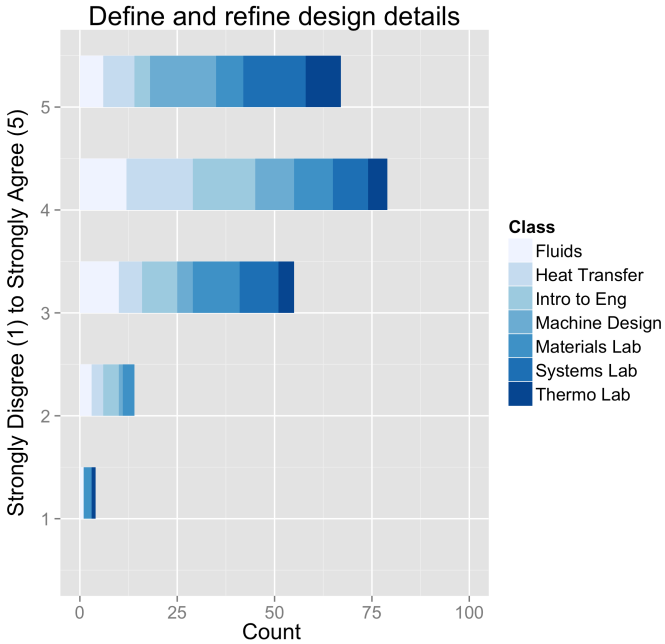

Figure 4. Student survey responses for defining and refining the design details. . Most students expressed that they "agree" that the design spine projects are effective at teaching "defining and refining design details."

A summary of student responses by project is shown in Figure 5. This summary indicates that the projects in Machine Design, Systems lab, and Thermodynamics lab were the most helpful for defining the design problem. For synthesizing knowledge the System lab, Machine design, and Heat transfer were the most useful. Students perceived the projects in Machine design, Systems lab, and Heat transfer as helpful for evaluating design alternatives. For refining the design they reported that Machine design, Systems lab, and Thermodynamics lab were the most helpful. And by experiencing the design spine, students believe they have learned the design process and each of its primary elements. The weakest response in the student survey is in regards to "evaluating alternatives."

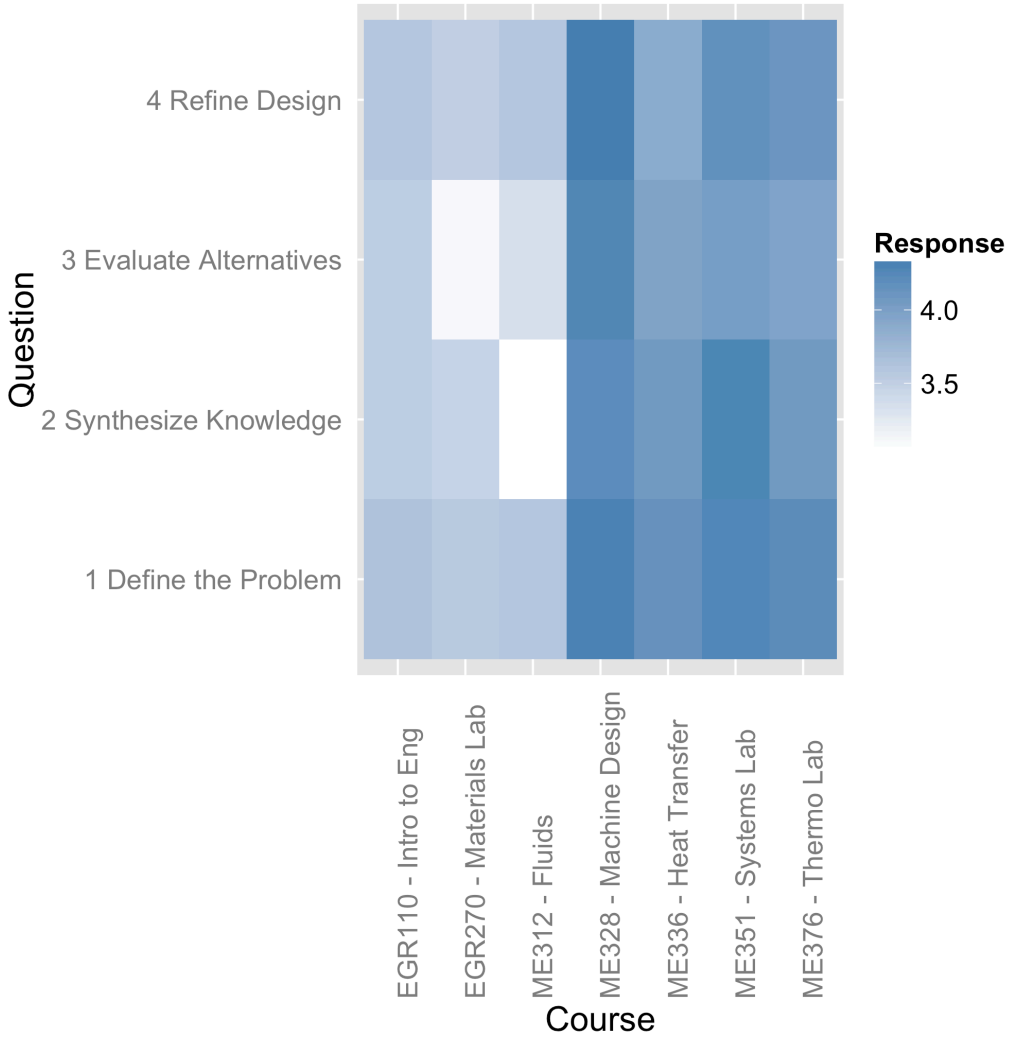

Figure 5. Student perception of the design elements in each class project. On average, the survey results show neutral to "strongly agree" that each project effectively teaches various elements of the design process.

The results of the survey show that most students believe the design projects are helpful to learn the design process. They have further identified several of the class projects were more helpful in building specific design skills. In the case of the project in Machine Design this outcome is not surprising since the class is designed to be taken in the Spring of the Junior year before the students enter the Capstone design course and focuses on the full design process.

Other courses like the *Introduction to Engineering* class were not ranked as highly by the students, however the class project was re-designed by the faculty in 2012 and the seniors who completed the survey experienced the older class project that may have been less effective as an introduction to the design process. In general the survey results provided feedback that will be used to identify opportunities for strengthening the design spine in the coming years.

Assessment of Specific Courses

Faculty members that teach each of the focus courses have outlined the design projects used in the class and provided a summary of how students have performed (instructor assessment). Survey results for the course are then presented. All of the projects discussed here involve student teams with two to four students per team. Some of the projects culminate with some form of competition, and some do not.

Introduction to Engineering (EGR110); Fall of first year**.**

Primary Fundamental Design Elements:

- Define the problem
- Synthesize knowledge to develop alternatives
- Evaluate Alternatives
- Define and refine the design details

The project provides students the opportunity to experience the entire design process including Design-Build-Test, but at a relatively superficial level.

Project: The central focus of this course is a semester-long design project. Students work to solve an open-ended challenge of the teams' choice from a selection of assistive technology projects. The challenges are designed to emphasize the essence of engineering and computer science; that is to solve a problem under a variety of constraints and multiple criteria. Successful completion of the challenge involves following through the design process from a conceptual design to a functioning concept-demonstration prototype, but also emphasizes non-technical aspects of engineering. The process involves innovative thinking, teamwork brainstorming, sketching, hands-on building, technical writing, and oral communication. To assist students with this process, the instructors have lectures, labs, and interactive discussions on topics such as brainstorming, the design process, technical writing, oral presentations, library research, and ethical conduct.

Instructor Assessment: Being first year students, they are not prepared to solve complex engineering problems. However, this project provides an excellent opportunity for students to learn the essence of the engineering design process. Faculty believe this project allows students to practice engineering design, but being an introductory project that requires little formal engineering training, students do not fully appreciate how realistic the experience actually is.

Student Survey: As shown in Figure 6 students surveyed perceived this project as being a somewhat effective educational experience for all aspects of engineering design. Students perceive the project in this course to be best at helping them learn the early aspects of the design process in problem definition and synthesis. The average survey scores were: define the problem 3.64, synthesize knowledge 3.52, evaluate alternatives 3.52, and refine details 3.60.

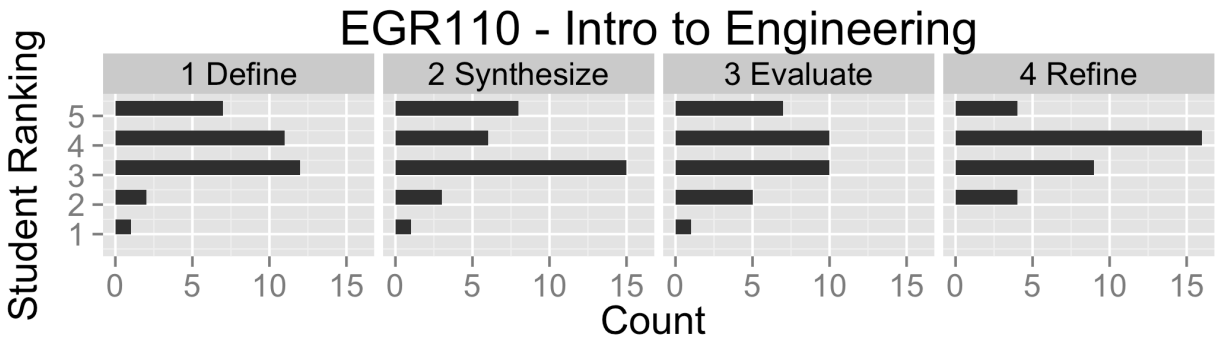

Figure 6. Histogram of student survey responses for Introduction to Engineering.

<u>Materials Laboratory (EGR270);</u> Spring of sophomore year
Primary Fundamental Design Elements:
Define the problem:
Develop a plan to solve a problem (answer an engineering question)
Evaluate testing alternatives:
Literature search

Project: The main features of Materials Laboratory are hands-on experiments in materials testing and processing. The "design content" of this course is a group-based Independent Laboratory exercise in which students study an engineering design question regarding materials topics such as creep or corrosion. In parallel with regular weekly laboratory work, about eight weeks of the semester are spent outside of class on this laboratory doing literature search, planning, and conducting the experiment. As part of the literature search, students must investigate relevant ASTM testing standards as well as other widely used professional resources such as the ASM Handbooks. The project culminates by reporting on the results in a formal presentation followed by a question and answer period. This provides the instructor the opportunity to assess how well the students designed and conducted the experiment.

Instructor Assessment: This project is believed to help students learn to study a problem independent of guided class-room lectures, to develop a plan and to execute the plan to answer an engineering question, and to interpret the results. Students evaluate alternatives by considering various ASTM standardized tests and adapting them to their specific needs. While the instructor is pleased with this project's outcomes, there is room to improve this experience. Currently, the project work-statement leads students to view this as another school assignment; in other words, they are doing the work for the instructor. They try to "figure out what the instructor wants." Revisions will be made in the work-statement to help students approach the problem as if they were a professional engineering answering a question for a client. This would require students to understand the importance of experimentation in engineering design rather than just performing another class exercise for the instructor.

Student Survey: As shown in Figure 7 students surveyed perceived this project as being a somewhat effective educational experience for all aspects of engineering design, but a neutral response for "evaluating alternatives." The project appears to offer the most value in the problem definition stage of design. The average survey scores were: define the problem 3.56, synthesize knowledge 3.47, evaluate alternatives 3.12, and refine details 3.50.

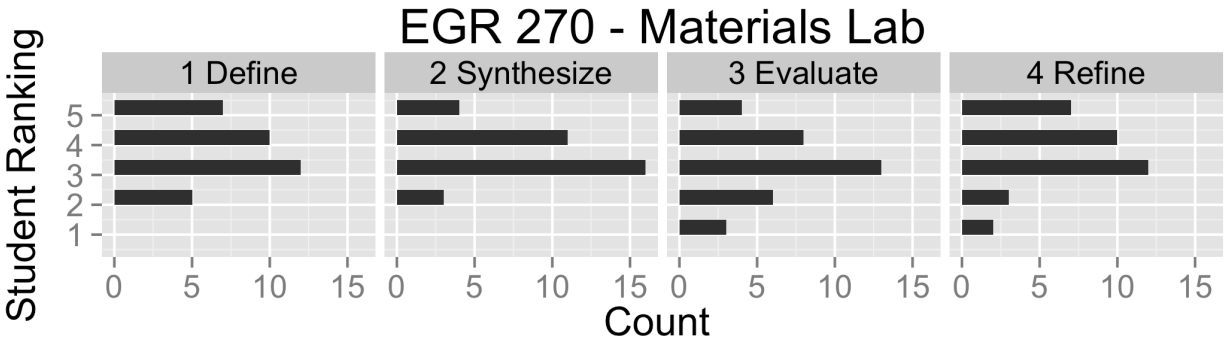

Figure 7. Histogram of student survey responses for Materials Laboratory.

<u>Mechanical Systems Laboratory (ME351)</u>; <u>Fall of junior year</u>
Primary Fundamental Design Elements:

Define the problem (set goals and objectives)
Synthesize knowledge to develop alternatives
Evaluate alternatives:
Primarily through testing

Project: Students learn how to interface with machines through a few different methods, including Programmable Logic Controllers, Motion Controllers, and LabVIEW. The skills learned are then applied to a student-identified project relating to assistive technology. Examples include designing a walker to sense and adjust to the height of stairs, an automatic transmission for a bicycle, and automated blinds that open or close based on the brightness outside.

Instructor Assessment: Many components of design are addressed, but the course stresses developing student creativity. Gathering information leads to appropriately set goals, and students are encouraged to reflect on how their research shapes the objectives, criteria, and constraints. Students are assessed on the appropriateness of their projects both in the context of the issue they are addressing and in the relevance to the course. The instructor believes that pedagogical improvements can be made in-part by making students more aware of how various project tasks relate to design. Starting this term, students will take a survey that explicitly states the design components emphasized in the course, and this material will be used to enhance student learning.

Student Survey: As shown in Figure 8 students surveyed perceived this project as being an effective educational experience for all aspects of engineering design; especially "defining the problem" and "synthesizing knowledge." The average survey scores were: define the problem 4.23, synthesize knowledge 4.29, evaluate alternatives 4.03, and refine details 4.17.

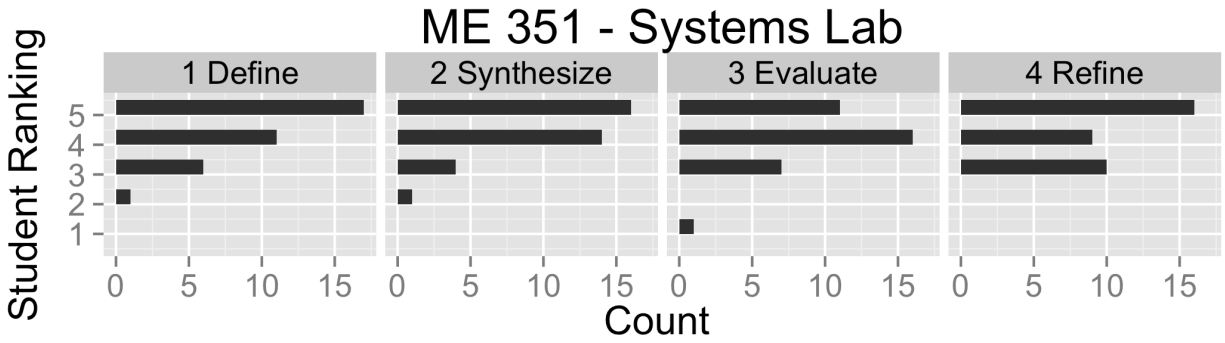

Figure 8. Histogram of student survey responses for Mechanical Systems Laboratory.

<u>Mechanics of Fluids II (ME312)</u><u>; Spring of junior year (second course in fluid mechanics)</u>
Primary Fundamental Design Elements:

- Synthesize knowledge to develop alternatives
- Evaluate Alternatives:
  - Analysis and mostly testing
  - Synthesize knowledge to select best alternative

Project: Students design, build, test, and demonstrate a hydro turbine from a kit that is provided to them. The kit consists of a plastic impeller shaped either like a fan or blower of approximately 4 inches in diameter. Students build turbines which use the water from a permanent test stand to lift a weight of one kilogram through a distance of three meters in the shortest time. This contest was a part of the Waterpower and Hydro conferences in the past and students from various universities in US and the world participated for prizes. The contest is no longer conducted by these conferences. However, for the last 20 years this has been part of Mechanics of Fluids II curriculum at the University of Portland. The cost of construction is quite minimal, less than ten dollars per team.

Instructor Assessment: The primary educational objective for this project is for students to learn that theory and analysis can at times take you only so far in engineering design, and that testing should be an integral part of the design process rather than an activity done at the end of the process for validation. Teams that test early and often and make incremental improvements are able to achieve the design goal. Teams that do not test before the competition usually fail to achieve the goals. In the design report, students reflect on what they should have done differently to have greater success. "We should have tested earlier" is the most common lesson learned. For the instructor, this is a sign of a successful educational project.

Student Survey: As shown in Figure 9 students surveyed perceived this project as being a somewhat effective educational experience for all aspects of engineering design with a near neutral response for "synthesizing knowledge." The students observed the project provided the most value for refining the problem. The average survey scores were: define the problem 3.59, synthesize knowledge 3.06, evaluate alternatives 3.34, and refine details 3.59.

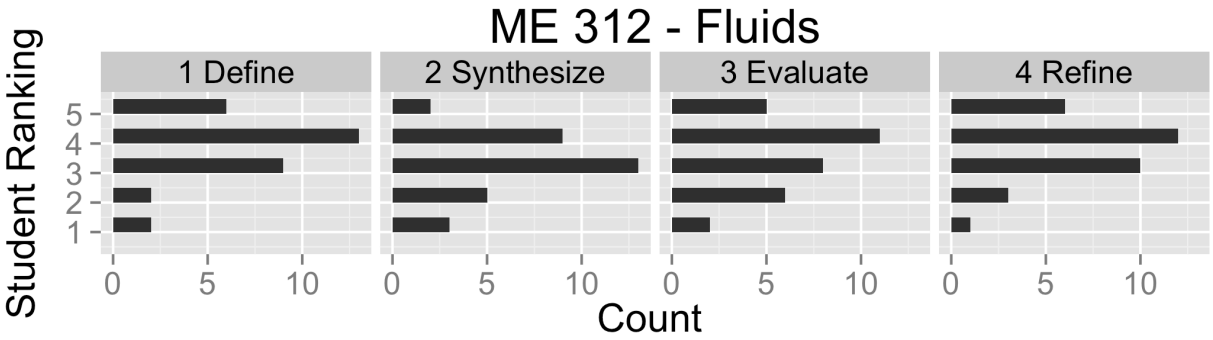

Figure 9. Histogram of student survey responses for the Fluid Dynamics course.

Heat Transfer (ME336); Spring of junior year
Primary Fundamental Design Elements:

- Synthesize knowledge to develop alternatives
  - Generate ideas and concepts
- Evaluate alternatives
  - Testing and analysis
  - Synthesize knowledge to select best alternative
- Define and refine design details (iterate through the design process)

Project: the project is a semester-long design-build-test project. It is introduced very early in the class with the stated objective of keeping a cup of coffee as warm as possible for one hour. Students experience the opportunity to iterate on the design over the course of the semester and during the last week of class they test their design that they have constructed. There is also an economic constraint: they may not spend more $20 on the project.

The first phase of the project is due shortly after the students learn the resistor circuit analogy for thermal analysis. They develop 2-3 design concepts and use a simple 1-D resistor analysis to optimize the design to minimize heat loss. This phase of the project reinforces the concepts learned in the course in a practice setting where material properties are unknown, cylindrical coordinates are critical, and assumptions about coffee temperature must be made.

As the course progresses the students move to the second phase of the project, where they select the best design concept and improve the modeling. They are required to add a transient analysis technique to the simple resistor analysis. This part of the project occurs after the students have learned about transient heat transfer methods, but many of the techniques are mathematically very difficult and this is the most challenging aspect of the project. In this phase of the project the students are encouraged to augment the theoretical analysis with preliminary experimental results to get a feel for accuracy in the analytical models.

The final testing day allows the students to write down the predicted temperature change for the coffee and compare it to the temperature change measured during class. The team that achieves the lowest temperature change in one hour of in-class testing is rewarded with bonus points on the project report. In general the students find the project to be a fun and practical application of the theoretical heat transfer knowledge they have gained during the course of the project.

Instructor Assessment: theory-based analysis is required in this project, not necessarily to predict performance, but rather to optimize the design. Final testing is done with all students present – so all students become aware of each other's design creativity. Through this project, students gain an appreciation for using analysis to optimize design and using testing to validate the analysis.

Student Survey: As shown in Figure 10 students surveyed perceived this project as being an effective educational experience for all aspects of engineering design. The project was most helpful for synthesizing knowledge, an outcome that is consistent with the instruction objectives of system optimization using heat transfer theory. The average survey scores were: define the problem 4.15, synthesize knowledge 4.06, evaluate alternatives 3.97, and refine details 3.88.

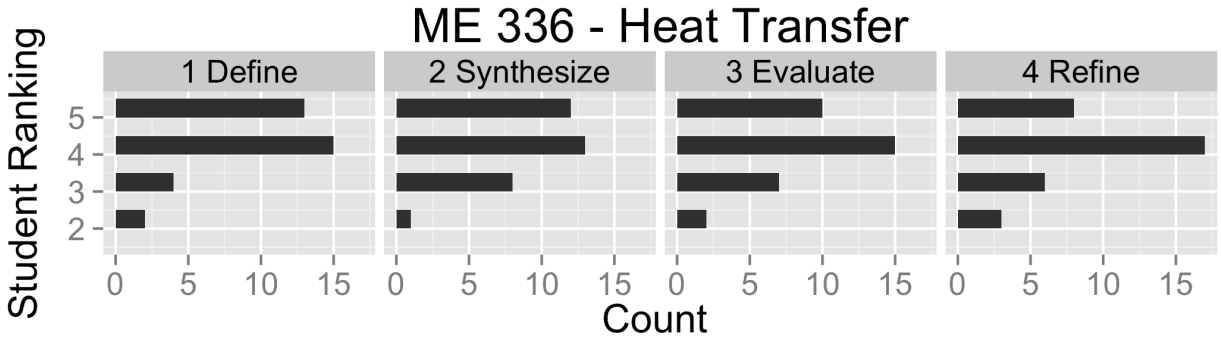

Figure 10. Histogram of student survey responses for Heat Transfer.

<u>Machine Design (ME328);</u> <u>Spring of junior year</u>
Primary Fundamental Design Elements:

- Define the problem
  - Establish criteria
  - Developing a plan to solve the problem
- Synthesize knowledge to develop alternatives
- Evaluate alternatives
  - Test subsystem function, test prototype
  - Analysis (power transmission system)
  - Synthesize knowledge to select alternatives
- Define and refine design details (iterate through the design process)

Project: This project is unique in our curriculum in that it mimics in several respects the expectations for capstone projects. It requires similar documentation (project plan, mid-project documentation, and a final design report). It also requires similar project management practices including formal team meetings with written agenda, maintaining an action item log, and providing the instructor concise weekly updates. These were introduced in the ME 328 project several years ago as a response from seniors who expressed a sense of being overwhelmed by "project and team management" more than the technical challenges. Providing juniors the opportunity to practice using project and team management tools equips them for the capstone project.

The technical side of the project requires students to design, construct, and test a vehicle to compete against other teams. Only material from a LEGO Mind-storm kit may be used (the same kits used by first-year students in the fall semester). The main functional design challenge is to select a single gear ratio to achieve two different requirements (a steep hill climb and quickly traversing a flat track). Before doing so, students must understand motor performance (torque and speed relationship). Students must also satisfy economic and safety criteria. In order to have an effective design, the students are required to synthesize their knowledge of power transmission, gear ratios, and motor performance. The most successful teams iteratively evaluate their design by integrating testing with analysis early in the project.

Instructor Assessment: Projects similar to this have been used for several years in this course. What the instructor has identified as being the primary design challenge for students is creating a plan to solve the problem; from the beginning, many seem unable to determine what engineering work is needed. Most students approach design linearly: determine best gear ratio, build vehicle, test, and then compete – with little detail about what is required to determine best gear ratio or what the purpose of testing is. After the plans are submitted, the instructor facilitates an open class discussion about what really needs to be done to solve the design problem. Through this process, students are led to clearly understand the challenging technical problems and to identify what knowledge is needed to solve them. Students then re-do their plans using this class discussion as the framework. This new plan usually includes clear and specific tasks of analysis, construction, and testing to solve design problems incrementally and iteratively.

Prior to this class, the students have experienced various elements of design. This project is their first opportunity to "put it all together" in a single design project.

Student Survey: Of all the projects in the design spine, this project is most intended to be a full design project, from planning through design, building and testing, preparing students for their capstone design course. The high survey scores shown in Figure 11 indicate the machine design project is very effective as an overall design experience. Students reported the project was overwhelmingly helpful in learning about all aspects of the design process. The average survey scores were: define the problem 4.31, synthesize knowledge 4.19, evaluate alternatives 4.28, and refine details 4.34.

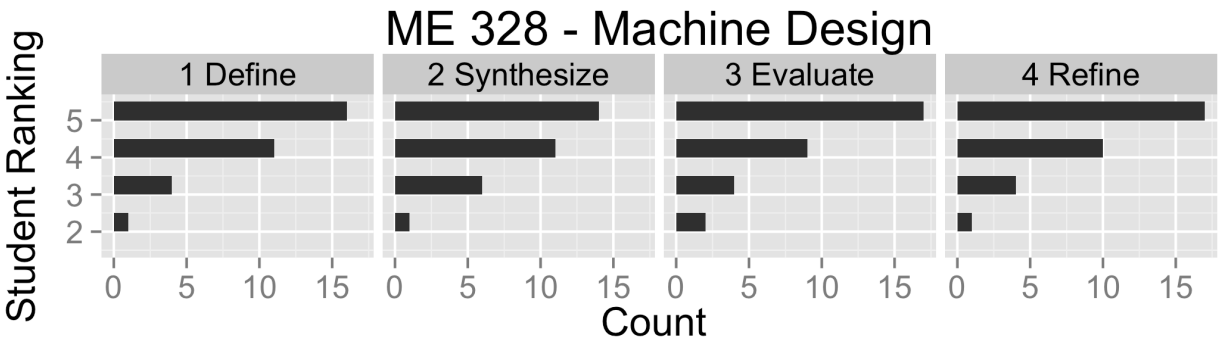

Figure 11. Histogram of student survey responses for Machine Design.

<u>Thermodynamics Laboratory (ME376); senior year</u>
Primary Fundamental Design Elements:

- Define the problem (establish criteria)
- Synthesize knowledge
  - Generate ideas and concepts
- Evaluate alternatives
  - Analysis
  - Testing
  - Synthesize knowledge to select the best alternative

Project: The final project for *Thermodynamics Laboratory* is a three week design project that encourages the students to iteratively design, analyze, and test a device to heat water. The course is typically taken during the senior year after completion of *Fundamental Thermodynamics* (ME331), *Applied Thermodynamics* (ME332), and *Heat Transfer* (ME336).

The primary goal is to determine, within given constraints, how to generate the largest change in temperature of 250 mL of water in three minutes. Students are given a 400 mL Pyrex® beaker and four standard birthday candles. They are allowed to use insulation and building materials, but they are not allowed to add more fuel to the system or do any thermodynamic work on the system during testing.

During the first week the students brainstorm 'boiler' designs that try to utilize the modes of heat transfer (conduction, convection, and radiation) to their advantage. They should be considering concepts to help transfer heat into the water from the candles while also minimizing heat loss to the environment. In parallel, fundamental thermodynamics can help them estimate the temperature rise that they could expect. At the end of the first week they should have built a concept that they believe will heat the water more than any other team. The second week is intended to be the time for evaluating design alternatives through testing. Inevitably, students will need to iterate on their design. Some students will find that most of their heat is being lost to the environment. Other students will find that their structure or insulation will ignite and cause a "raging fire." At the end of the second week, the students will have iteratively analyzed and built systems that they believe will be able to heat the water more than any other team. The last week culminates in a 'boil off' competition where each design is tested and compared against one another for the largest change in temperature.

Instructor Assessment: The students respond very well to this project. It is an open-ended, creative competition that forces them to formulate problem statements and specifications. In general, teams with more analysis during the design iterations fair better during the competition. It also gives the students a chance to see first-hand the relative impact of the heat transfer modes, and the feasibility of transferring heat via multiple modes.

The final deliverable is a formal project report including a discussion of the design process, analysis, testing, and results. As successful as this project is, it is possible that more freedom with the design choices could help the students realize more potential for heating the water. For example, if we allow them to use different vessels they may be able to appreciate the importance of material properties like thermal conductivity. Students who choose to use a larger vessel may be able to appreciate the importance of surface area. In a sense, allowing for more options during the design process will most likely result in more solutions.

Student Survey: As shown in Figure 12 students surveyed perceived this project as being an effective educational experience for all aspects of engineering design. The students reported the project was most successful at helping them learn to define the problem and refine the design. This is consistent with the instructional objective that they will focus on verifying performance of the design experimentally and refine the design as appropriate. The average survey scores were: define the problem 4.21, synthesize knowledge 4.05, evaluate alternatives 3.95, and refine details 4.11.

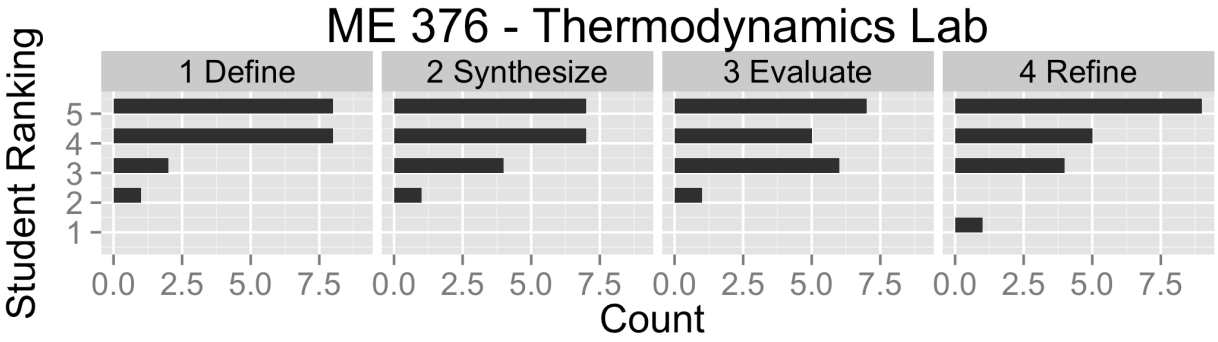

Figure 12. Histogram of student survey responses for Thermodynamics Laboratory.

Lessons Learned

The projects introduced in the first two years of the curriculum were perceived by the students as being less beneficial than projects in junior and senior level courses. The authors believe this is not due to the inherent differences of the projects, but rather that juniors and seniors are better prepared to learn from open-ended design experiences. In other words, the course work and design projects in freshmen and sophomore courses prepare students for a better educational design experience as juniors and seniors. We believe that allowing students to practice various aspects of engineering design throughout the entire curriculum is an effective and important process for teaching design, but that the emphasis during the first two years should be on preparing students to solve engineering problems with some (limited) practice solving open-ended design problems. During the junior and senior years, after completing fundamental engineering science courses, is when students are best able to learn the design process by practicing it more fully.

Incorporating Lessons Learned

As a result of developing a design spine and the evaluating survey results, we are in the process of making revisions to our courses and projects. We are hoping to develop very simple projects that can span two or more sophomore-level courses; each course addressing certain design elements of the project. It is hoped that such small-scaled projects will allow faculty to guide students by incrementally stepping through the design process. It is also hoped that such multi-course projects will help students appreciate that engineering is a multi-discipline field not segmented along clear boundaries (like courses sometimes are). Although individual faculty are hoping to make improvements in their course projects (as discussed in the respective courses above), overall, the faculty are satisfied with the junior and senior level projects for now.

Map for developing a design spine

We recommend the following steps regarding developing a design spine. The entire program faculty should be involved with this as this process involves an evaluation of the entire program curriculum. This must be a team effort:

- Identify or define in writing what "engineering design" actually is with respect to your program. The ABET definition is a good place to start.

- Identify the elements or "steps" of engineering design appropriate for your institution. Each individual and each group of faculty has their own perspective.
- Identify in your existing curriculum where various elements of design are already being addressed. Existing homework problems, specific lectures, course projects, etc., may already incorporate many elements of design.
- Survey seniors to evaluate if their perceptions are similar to the faculty perspective. We recommend in addition to asking students to evaluate individual projects or assignments, also ask the students to evaluate the overall curriculum itself – how well do the student feel they achieved the various elements of design regardless of how or in what class they learned it. Also ask for comments, not just numerical scores.
- Having full design-build-test opportunities in the junior year was shown to be a significant part of our design-spine. As much as reasonably possible, at least one project at the end of the junior year should mimic your program's expectations for capstone projects. This should including requiring similar documents and project management expectations (see the discussion for Machine Design (ME328)). By end of the junior year, students have most of the technical tools needed for a working on a substantial design problem. Allowing them to apply those tools in a semester-long open-ended design project utilizing project management methods prepares them for more challenging capstone design projects.
- Review existing curriculum and identify opportunities to strengthen design. This need not require new courses, but may involve introducing new assignments or design projects within existing courses.
- Annually, re-evaluate by surveying seniors and identifying opportunities for improvements.
- Finally, we recommend making the design spine well known to the students, don't keep it a secret. The more clearly students see individual assignment and projects as part of a larger pedagogical plan, the more they likely they will take ownership in it.

Conclusions

Having a design spine that incorporates various elements of engineering design throughout the four-year curriculum can be an effective method for teaching engineering design. Even if individual projects do not address all aspects of design, each project can make a significant contribution to pedagogy of design. The starting point for the creation of our design spine was to define what design is and to identify where various design elements were already being taught. Student surveys were used to evaluate how well the curriculum teaches various design elements, and the surveys will be used to guide curricular and project changes.

The survey results indicate that the students are learning the engineering design process, and each class project has its strengths and weaknesses. There are many opportunities for improvement, and the faculty will be addressing these in the near future. Changes may include revisions to existing projects, adding new projects or replacing current projects, and integrating projects across courses. Changes will also include clearer communication with the students so that they can better appreciate how individual projects are helping them learn the design process.

The research team believes that the project will benefit from continued assessment and plan to collect survey data from senior students annually to understand how successful enhancements will be over time. As the design spine matures additional assessment measures may be added in specific courses or in the form of individual alumni interviews.

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