

## **AC 2007-693: USING THE ENGINEERING DESIGN PROCESS TO RE-ENVISION MULTIDISCIPLINARY EDUCATIONAL EXPERIENCES FOR ENGINEERING STUDENTS**

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# Using the Engineering Design Process to Re-Envision Multi-Disciplinary Educational Experiences for Engineering Students

## Abstract

Accredited engineering programs need to show that their students learn how to effectively “function on multi-disciplinary teams.” This skill is important not only for accreditation but also to employers and to educators themselves, who understand the changing world of engineering work. In the summer of 2005, the College of Engineering at Montana State University embarked on a study of multi-disciplinary engineering education within the college. This study followed the engineering design process. After an information-gathering stage, an ad-hoc cross-disciplinary team of faculty developed and refined multi-disciplinary learning objectives, criteria for evaluating alternatives, and several alternatives for the best local option for multi-disciplinary learning. The alternatives were then evaluated using a selection matrix. The top alternatives were further refined and taken to the broader faculty for comment. We are now at the stage of implementing our chosen solution. Using the engineering design process for the year-long study was surprisingly successful in developing buy-in from faculty and administration. This paper presents in a fair amount of detail our process and results. This process could be useful for other engineering programs considering curriculum changes.

## Introduction

Curriculum reform in higher education is a difficult process, and engineering education is no exception. Making curricular changes is time-consuming and can be polarizing and frustrating. Gaining consensus from various constituencies, including students, faculty, and industry partners, is difficult at best. Fully understanding the inherent difficulty of the task, Montana State University (MSU) faculty undertook a study to determine how to reform our engineering curriculum to offer students a multi-disciplinary experience. We approached the study by explicitly following a process that would be widely recognized as an engineering design process. Our thought was that using an engineering design process, a familiar one to faculty, would help to validate the work and gain faculty buy-in.

A survey of the titles and abstracts of *Journal of Engineering Education* papers published in the last dozen years showed many publications whose purpose was to discuss course and curriculum changes<sup>1,2,3,4,5,6,7</sup>. Although this search is not comprehensive, we found that none of these publications about course and curriculum reform specifically described a process that mimicked an engineering design process.

In this paper, we describe how we organized and conducted our curriculum study around an engineering design process, and how doing so not only helped us to approach curricula in the same thorough manner in which engineers approach technical problems but also helped us

build faculty consensus. The approach could easily be used by other engineering programs and colleges re-envisioning their curricula to meet the demands of the “Engineer of 2020.”<sup>8</sup>

Numerous models of engineering design can be found in the literature.<sup>9</sup> But even though the engineering community has not universally adopted any one model, the main steps and activities are common across most of the models. For this project, we followed the following steps:

1. Identify and define the need
2. Gather information
3. Establish design objectives
4. Generate alternatives
5. Converge to a final solution
6. Implement final solution

The convergence step (#5) derives from prior work by the first author in product development.<sup>10,11</sup> In this “set-based” approach, rather than select a “best” alternative from the set generated, the team eliminates the clearly inferior alternatives. They then gather additional information on the remaining alternatives, while developing them further, until one or more can be determined as clearly inferior and safely eliminated. The process continues until a final solution remains. Such an approach eliminates the problem of making early decisions without enough knowledge, and allows time for proper consideration and input. Each of the following sections corresponds with a step in the engineering design process outlined above.

### **Identifying and Defining the Need**

Montana State University has a strong reputation for developing engineering graduates with solid grounding in engineering fundamentals and strong technical skills. Part of that tradition is a capstone design experience within each program in the senior year. Each program has evolved its own senior design course over the years to suit its particular curricular needs. Typically projects have been team-based with representation from within the discipline exclusively.

A few years ago, the College of Engineering initiated a program to offer a multi-disciplinary design opportunity for the senior design project. The “No Walls” program had students take an engineering design course (ENGR 401) offered through the general engineering program as a substitute for their discipline’s capstone course(s). The faculty coordinator identified the appropriate disciplines as dictated by the project requirements, and recruited students (largely through the capstone instructors) to enroll in ENGR 401. The faculty coordinator would then recruit advisors for the projects from the disciplines represented (thus teams had 2, 3 or more advisors), and negotiate project deliverables for the team sufficient to satisfy the requirements of the students’ home capstone course requirements. In the first year, a handful

of projects were tackled in this fashion with some success, so in subsequent years the program was scaled up to increase the number of projects and students participating.

Over the next two years, the overhead of coordinating a large number of projects became overwhelming. Every project was unique, with unique team composition and advisory structure. The specific requirements for each project were negotiated each semester between the respective capstone instructors, advisors, and students. This was a time consuming and often confusing process. For example, it was often unclear who would decide the students' grades (the advisors or instructor) because the model was different for every project. Some students did not even know in which course they were enrolled midway through the semester. Furthermore, many students felt they had significantly more requirements placed on them than their classmates working on single-discipline teams. For example, a team comprised of Industrial Engineering and Mechanical Engineering students was required to prepare and present a poster at the Mechanical/Electrical Engineering Design Fair (a requirement of the ME course but not the IE course) and to make a 30-40 minute formal presentation to students and faculty (a requirement of the IE course but not the ME course). Also, many students commented that the overhead of working with students from other programs seemed significantly greater than for their counterparts working in single-discipline projects and enrolled in the same course, so the overall workload was perceived as higher. And finally, while some projects were very successful, many were not. As one faculty member commented, "When multi-D projects succeed, they succeed spectacularly. But when they fail, they also fail spectacularly." In exit interviews, many graduating seniors cited multi-disciplinary design as their worst College experience.

Therefore, the College embarked on a study to determine a best path forward with respect to multi-disciplinary engineering. The authors were asked to lead the study.

### **Gathering Information**

Before diving into solutions, we conducted an investigation to define what problem we really want to address and identify possible solutions. These activities included: researching multi-disciplinary programs at other institutions, in-house comparison of curricula to identify existing multi-disciplinary courses and experiences, understanding the current state of design instruction within the College via interviews with design instructors, and discussions with advisory board members.

#### ***Other Multi-disciplinary Design Courses and Programs***

As a first step, we searched the engineering education literature for programs and courses on multi-disciplinary design. Many of the articles describing multi-disciplinary courses have a product-development focus.<sup>12,13,14,15,16,17,18</sup> Our objectives seemed somewhat unique in that we wanted to include all College departments in our ultimate solution, even those whose disciplines typically do not participate in a product development (civil and chemical engineering, for example). Given that our College has five engineering programs, two engineering technology programs, and a computer science program, the literature did not provide much guidance.

We also identified a number of engineering colleges through personal contacts and web search that advertise a multi-disciplinary design program, and interviewed the directors or

faculty involved. From this background work, we concluded that about half of all engineering colleges in the U.S. have some sort of multi-disciplinary design program, particularly at the capstone level.<sup>19</sup> However, it appears that every program is unique, even in their definition of multi-disciplinary. For example, some believed that “multi-disciplinary” meant including disciplines outside engineering, whereas others did not. We were not able to identify a universal model for the structure of multi-disciplinary design programs, and concluded that successful multi-disciplinary design programs are uniquely designed for the culture and environment of the particular institution. This work, though, turned up a number of ideas that we could possibly leverage for Montana State University.

#### ***Curricular Tabulations***

In parallel, we accumulated the individual program requirements for all of the engineering and technology programs within the College. This analysis revealed that while many programs take courses common to other programs, there is no single engineering course that all engineering and computer science students take (all students take calculus, general physics, freshman composition, and communication, but these are outside the College and with the rest of the university).

There are also a number of “majors only” course offerings on topics that students from other programs take. For example, both mechanical engineering and chemical engineering offer a discipline-specific introductory thermodynamics course, and a third course is available for other majors. Thus students in mechanical engineering, for example, never get the chance to interact with other engineering disciplines on a topic germane to their home discipline. Some of these courses are potential opportunities to introduce multi-disciplinary elements.

#### ***Design Instructor Interviews***

The next step in our investigation into the landscape of multi-disciplinary education within the College was to interview all of the design instructors. Most of the programs have only one 3- or 4-credit course (or equivalent number of credits in a course sequence) in design, and it is the capstone course. Mechanical engineering has an introductory design course that is a prerequisite to the capstone, while mechanical engineering technology’s capstone sequence is 6 credits across two courses. Thus, *most students graduate from the College with only one beginning-to-end design experience*: their capstone project.

We confirmed that the number of credits, course structure, course requirements, and course content differ significantly across programs. This was often cited as the reason that the current multi-disciplinary program was not more successful. However, we learned from the interviews that these differences derive from significant, legitimate differences in the pedagogical objectives. For example, mechanical engineering and electrical engineering capstone objectives focus on the design of a device, from defining customer needs through design and analysis to producing a paper and/or prototype design. Civil engineering capstone objectives, on the other hand, focus heavily on project procurement, project management, and construction drawings and specifications. The “design process” presented to civil engineering students bears little resemblance to that taught to mechanical engineering students. Chemical and biological engineering and industrial engineering programs are different still, since they focus on process design with economic analysis playing a central role. Thus, each program’s capstone courses have been designed to meet specific curricular

needs of that program. It may be possible to align the objectives of each of the capstone courses; however, each program had legitimate pedagogical reasons for the design of their capstone experience (e.g., integration of knowledge from subspecialties within a given discipline). Thus, *we concluded that attempting a college-wide multi-disciplinary design experience in the capstone would simply not be appropriate.*

The capstone courses do share some common objectives. Particularly, all focus on working effectively on teams, oral and written communication, design process, and project management. However, the amount of formal instruction and direct intervention varies widely across the College for several of these objectives (e.g., project management), and is uniformly low on at least one (teamwork). Also, creativity is not heavily emphasized in any of the design courses.

#### ***Advisory Board Interviews***

We also interviewed the Mechanical and Industrial Engineering departmental advisory board and about eight members of the College's Engineering Advisory Council about what they envision of multi-disciplinary design. Responses were far from uniform, with at least one person indicating that the value of multi-disciplinary design at the undergraduate level was unclear. The themes that came out from the interviews were:

- “Multi-disciplinary” means different things to different people. To some people, it means two or three engineering disciplines working together. To others, it means taking manufacturing considerations into account. To still others it means including non-engineering disciplines such as business, marketing, and industrial design.
- It is important for graduates to be able recognize trade-offs that occur across traditional disciplinary boundaries. They must be able to take a “systems perspective” of the projects on which they work.
- They must be able to appreciate differences in the perspectives of others.

Industrial advisory board members indicated that a multi-disciplinary experience need not occur in the capstone, so long as students graduated with these skills. When pressed on the relative importance of these multi-disciplinary engineering skills, the consensus seemed to be they were important, but not as important as technical skills.

#### **Establishing Design Objectives**

From the groundwork investigation, Sobek developed an initial set of objectives for the multi-disciplinary program, whatever shape it may take. These objectives were presented to a cross-disciplinary advisory team that included representatives from all programs (except Construction Engineering Technology) and the Dean's Office, and were refined through several iterations.

The adopted objectives of the College's multi-disciplinary initiative are to build in our graduates the capacity to:

- View engineering projects from a systems perspective.
- Recognize and appreciate trade-offs across disciplinary perspectives.

- Communicate technical and other trade-offs, and negotiate satisfactory resolution.
- Generate creative, integrated and effective solutions collaboratively.

The first three objectives derived primarily from interviews with industrial advisory board members. Even though there was a diversity of opinions on the definition of “multidisciplinary” (as explained above), when probed about why such an experience is valuable, very consistent responses appeared. Nearly every respondent used the term “systems perspective” or similar, meaning that they desire engineers who understand how their piece fits within the broader picture. Many mentioned the imperative for engineers to not just represent their own perspective in team situations, but to also appreciate the perspectives of others on the team. The term “trade-offs” was introduced from the design research literature to capture the essence of the respondents’ arguments. The second and third objectives then attempt to convey the dual role of representing one’s own perspective while seeking to understand others’ perspectives. The last bullet item attempts to capture in a single phrase the overriding objective of the various capstone design instructors, which is also consistent with the overall desires expressed by the industrial advisory board members.

We also decided that ultimately our goal would be to include disciplines outside the College in our multi-disciplinary experiences for students; however, we would begin with engineering, engineering technology, and computer science programs.

### **Generating Design Alternatives**

Also from the initial groundwork, in collaboration with the advisory team, we generated seven alternative approaches to accomplish the above objectives. The seven alternatives are described briefly in Table 1.

### **Convergence to a Final Solution**

The advisory team evaluated the set of alternatives against the following criteria, developed from concerns raised in interviews with College design faculty:

- Ability to meet multi-disciplinary objectives
- Complementary to curricular objectives of participating programs
- Ability to achieve good fit between project needs and disciplines represented
- Ability to achieve consistency in expectations/requirements of students
- Implementation and support cost (actual dollars)
- Reasonable faculty load (e.g., faculty hours required per student)
- Acceptance among College faculty
- Space needs

Table 1: Alternatives for Meeting Multi-Disciplinary Program Objectives

<i>Alternatives</i>	<i>Description</i>
A. Ad hoc	<ul style="list-style-type: none"> <li>• Design course instructors organize multi-disciplinary projects on an ad hoc basis. Instructors coordinate among themselves.</li> <li>• Similar to current program.</li> </ul>
B. College capstone	<ul style="list-style-type: none"> <li>• All engineering and computer science students enroll in the same capstone course (ENGR 4xx).</li> <li>• Course is team taught, with each program represented.</li> <li>• Projects are a mix of single and multi-disciplinary; students assigned according to project needs.</li> </ul>
C. Junior-level design course	<ul style="list-style-type: none"> <li>• College-wide design course that prerequisites into program capstone courses.</li> <li>• Topics: design process, creative design, project management, team work, business basics, product / project lifecycles. (possibly could have ethics and oral/written communication)</li> <li>• Multi-disciplinary project assigned.</li> </ul>
D. Freshman course	<ul style="list-style-type: none"> <li>• “How Things Work” – show the interdisciplinary nature of engineered products, engineering projects, and their manufacture/construction.</li> <li>• Hands-on laboratory (product teardowns, field trips)</li> </ul>
E. Suite of Design Electives	<ul style="list-style-type: none"> <li>• Create a suite of design electives organized around “natural groupings” of disciplines. For example.,                             <ul style="list-style-type: none"> <li>○ Integrated Product-Process Development</li> <li>○ Integrated Building Design and Construction</li> <li>○ Humanitarian Process Engineering</li> </ul> </li> <li>• Students take as professional elective; some programs may allow substitution for the capstone.</li> </ul>
F. Curriculum infusion	<ul style="list-style-type: none"> <li>• Create a set of multi-disciplinary courses within the College. Could be existing courses revamped or new courses.</li> <li>• Institute a graduation requirement to take a certain number of multi-disciplinary credits.</li> </ul>
G. Co-op / Internship program	<ul style="list-style-type: none"> <li>• Institute a required coop/internship for every graduate.</li> <li>• Must reflect on importance of multi-disciplinary skills observed in others or acquired.</li> </ul>

The evaluation matrix shown in Table 2 displays a summary of the advisory team’s evaluations. The current ad hoc system (Alternative A) was held as a baseline, and each alternative was then evaluated relative to the baseline. The scoring system reflects the level of agreement/disagreement of the advisory team, as indicated in the Table note. One of the alternatives (Alternative D) was viewed by the team as non-comparable to the baseline. But since it received a strongly favorable response from the advisory team, it was kept as an alternative. Also, team discussion generated a number of combinations of alternatives, although none of these received strong team support, so were not added to the mix.



Table 2: Evaluation Matrix of Alternatives

<i>Criteria</i>	<i>Alternatives</i>						
	<b>A*</b> <b>Current Ad Hoc</b>	<b>B</b> <b>College Capstone</b>	<b>C</b> <b>Jr. Design</b>	<b>D</b> <b>Frosh Course</b>	<b>E</b> <b>Design Electives</b>	<b>F</b> <b>Infused Curr.</b>	<b>G</b> <b>Coop/ Intern.</b>
Ability to meet <b>multi-D objectives</b>	0	2	2	**	2	1	0
Complementary to <b>curricular objectives</b> of participating programs	0	-2	1		0	1	2
Ability to achieve good <b>fit</b> with disciplines represented	0	2	2		2	2	0
Ability to achieve <b>consistency</b> in expectations/requirements of students	0	2	2		2	2	-1
Implementation and support <b>cost</b> (actual \$)	0	-2	-1		-2	0	-2
Reasonable <b>faculty load</b> (e.g., faculty hours required per student)	0	-2	-1		-2	1	0
<b>Acceptance</b> among COE faculty	0	-2	-2		1	1	0
<b>Space</b> needs	0	-2	0		-1	0	2
<b>SCORES</b>	<b>0</b>	<b>-4</b>	<b>3</b>		<b>2</b>	<b>8</b>	<b>1</b>

**Scoring:** +2 = better than baseline (strong team agreement), +1 = better than baseline (some team disagreement), 0 = equal to baseline, -1 = worse than baseline (some team disagreement), -2 = worse than baseline (strong team agreement).

\* Baseline alternative.    \*\* Not evaluated because it is not directly comparable to the baseline alternative.

The three weakest alternatives from the evaluation matrix were eliminated (see Table 2), reducing the set of alternatives to four: (1) a junior-level design course, (2) design electives, (3) infused curriculum, and (4) co-op/internship. We then began conversations with a broader group of faculty to (a) give them the background and rationale for the direction we were taking to hopefully build some consensus, and (b) to obtain their feedback on the set of alternatives. Sobek met with the department heads and a few key faculty members in each program in addition to the advisory team. After reviewing the process leading to the four remaining alternatives under consideration and describing the alternatives in some detail, Sobek asked the participants to discuss the pros and cons of each alternative from their

program's perspective. They were then asked to identify which one or two alternatives they favored. From these conversations, *all* participants identified one of two alternatives as clear favorites: a junior-level design course and a suite of design electives. However, there was not a strong consensus as to which of the top two was preferred, so both alternatives were developed in greater detail.

We found it interesting that “infused curriculum” received the highest numerical score (see the Evaluation Matrix in Table 2), yet people did not think it was the best alternative, largely because of the logistics involved in administering the program. This outcome showed that we had not accounted for all contextual variables in our criteria, and also showed us the importance of using more than just an evaluation matrix in our decision-making. Our conversations with faculty provided rich information to add to the mix.

*Adding More Detail to the Remaining Alternatives.*

One of the alternatives emerging as a top runner was to implement a required junior-level design course for all College of Engineering students. The course would introduce students to design topics such as design process, creative design, project management, and teamwork while highlighting the skills needed to work in a multi-disciplinary environment. Students would also complete a multi-disciplinary group project as a major component of the course. Other topics could possibly be incorporated, such as ethics and communication skills.

The course would become a prerequisite to the capstone courses in each program. Thus the instructor would need to coordinate with the capstone instructors, in essence treating them as customers, in designing and refining the course.

Multi-disciplinary design content would be incorporated into appropriate lecture topics throughout the course. Each semester could have its own theme for the design project, such as energy conservation, assistive technology for the elderly or impaired, or economic development for the third world. The instructor would have to make the team assignments to ensure multiple disciplines are represented on each team. The teams would then choose their own project within the semester's theme, possibly evaluated by a panel of judges.

Given the scale of the class, most likely the course would require a lecture plus recitation format. Lectures would meet twice a week in a large lecture hall; recitations would meet once a week in smaller groups of 20-25. Significant teaching assistant support would be needed.

The second of the top two alternatives was a suite of design elective courses under the general ENGR rubric designed around natural clusters of disciplines. The clusters would be modeled after the kinds of disciplines that typically work together in industry. For example:

- Integrated product/process design: mechanical engineering, mechanical engineering technology, industrial engineering, business
- Design-Build in construction: civil engineering, construction engineering technology, architecture
- Humanitarian engineering: chemical and biological engineering and civil engineering

- Intelligent machines: computer science, electrical and computer engineering, industrial engineering, mechanical engineering
- Biomachines: chemical and biological engineering, mechanical engineering, electrical and computer engineering

Students would take one of the courses as a professional elective, not as a substitute for the capstone (although, perhaps, some disciplines may allow a substitution). The courses would likely be project-based. Most of the courses would require some technical content be taught through lectures, depending on the nature of the course. Throughout each, the multi-disciplinary design objectives would be emphasized.

As an implementation path, we would most likely develop and offer one or two courses per year. After three or four years, having tested, refined and proven the courses, we could make multi-disciplinary design “required” (i.e., every student takes one design elective).

*Gathering More Information from Constituents*

Before returning to constituents to gather more input, we developed a detailed plan for choosing and testing the final alternative. In July 2006, a team of six from MSU participated in the Engineering Educators Leadership Institute sponsored by the National Academy of Engineering’s Center for the Advancement of Scholarship in Engineering Education.<sup>20</sup> The team included the authors of this paper, the dean of engineering, the assistant dean, and two department heads. At that event, we developed the following timeline for implementation.

August 2006	Sobek presents the two top alternative strategies at department faculty retreats; solicits comment and buy-in.
September 2006	Present the alternatives to the College’s Curriculum Committee and request a recommendation.
October 2006	Curriculum Committee makes recommendation to Dean; Selection of alternative
Nov-Dec. 2006	Dean recruits an instructor; instructor develops pilot course, publicizes course, and recruits students
Spring 2007	Offer pilot course
Summer 2007	Assess pilot course, and decide future direction

At the department faculty retreats in August 2006, Sobek and the College dean presented detailed descriptions of the two top alternatives and elicited comments and discussion with faculty. The input was incorporated into the descriptions of the alternatives before this information was passed on to the college curriculum committee.

The curriculum committee recommended a pilot test of the junior-level design course in the spring 2007 semester, and also that departments be encouraged to develop multi-disciplinary electives.

In order to determine our success at meeting the multi-disciplinary objectives, we began developing a rubric, which will be a performance measure for an individual’s performance on a multi-disciplinary team (details are reported in a separate paper in these proceedings by

the same authors). This rubric was pilot tested at the end of autumn semester 2006 and will be used again spring 2007 in the new course.

## **Lessons Learned**

Curriculum reform is not easy to accomplish, particularly when it cuts across many programs with different goals. We realize that the effectiveness of efforts to reform curricula is heavily dependent on the local landscape; however, our model of using the engineering design process offers several advantages over other approaches.

*A familiar process:* Openly and explicitly using an engineering design process, including identifying constraints and alternatives and evaluating alternatives in light of constraints represents a familiar and revered process to engineering faculty.

*An open-ended solution:* The design process also requires an open-ended solution rather than a pre-determined solution. For example, the amount of variance in the program goals and objectives for program senior-level capstone design course actually surprised us. We had assumed that the failures in the previous “No Walls” program were partly a result of structural issues like difference in number of credits when, in fact, the difference in number of credits was simply an artifact of the difference in deeply held goals and objectives. Faculty in every program were adamant that changes in the senior capstone would compromise program goals, and when this became obvious, through our evaluation of alternatives, it became clear that we would need to make changes somewhere else in the curriculum. This flexibility garnered respect for our process. In fact, at one of the faculty retreats in late summer of 2006, a particularly opinionated faculty member noted his respect for the approach taken for this project, commenting that he had expected that we had a pre-determined solution early on in the study, but we had actually listened to faculty input.

*Faculty Buy-In:* Partly as a result of the first two points above, our process developed a surprising level of faculty buy-in. We are convinced that every faculty member in the college is aware of our process and has had a chance to offer input on several different occasions. This level of faculty buy-in bodes well for the sustainability of our new junior-level course. Furthermore, the new course is currently being viewed as a service course to the discipline-specific capstone courses, so a strong feedback mechanism from the capstone course instructors to the new multi-disciplinary design course instructor is currently being designed.

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