2006-869: USING PRINCIPLES OF DESIGN TO DEVELOP A CAPSTONE COURSE

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Abstract

Developing a senior-level capstone course is well-suited to the application of a structured design methodology. Specific “customer needs” that such a course should fill can come from ABET criteria, department objectives, and industry. Not only does such a structured approach help in identifying course content, but it also provides a means of measuring success. A design methodology that maps customer needs to specific metrics for a course provides an efficient assessment vehicle for verifying compliance with ABET outcomes and department objectives. This paper discusses how such a structured design approach can be used to design (or redesign) a capstone course in mechanical engineering.

Introduction

The engineering design process is a powerful tool for creating solutions to customer needs. Although application of the design process is often limited to the creation of new products, it could serve as an effective problem-solving tool in many other situations. For example, Pauley et. al.[1] proposed using the design process to aid in curriculum improvement at Penn State University. This paper presents an approach for applying the design process to the design (or redesign) of a senior capstone design course.

The author joined the mechanical engineering department faculty at Brigham Young University - Idaho in January of 2003. At that time BYU-Idaho had been a four-year university for less than three years (prior to that time the school had been a two-year institution known as Ricks College). As a consequence of the transition from a two-year college to a four-year university, many new junior and senior level courses were being developed, including courses in mechanical engineering. Among the new courses that were developed was a senior-level capstone design course. Although the structure of the course has appeared to serve the students and the project sponsors quite well thus far, a structured approach for determining the best format for the course was not followed. This paper illustrates how the design process could be applied to determine the best structure for such a course. Since the initial structure of the capstone course at BYU-Idaho has already been established, the process presented in this paper serves as a method to review and redesign the existing course structure.

The design process that is used throughout the paper is similar to that presented by Ulrich[2] (see Figure 1). Details of each of the design steps are presented in the following sections.

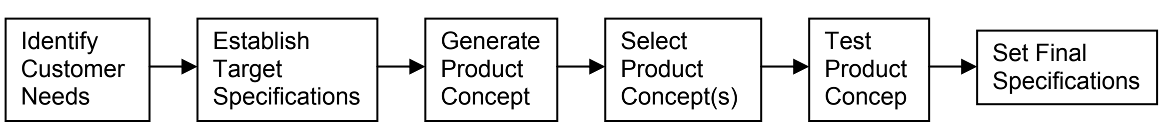

Figure 1. Design Process, Adapted from Ulrich[2].

Identify Customers Needs

One of the reasons that a capstone design course is particularly well-suited for the application of a structured design methodology is that the course typically serves several different customers. It is important that the capstone course be structured in such a way so as to meet the needs of all of its customers. The major customers of a capstone design course, along with a description of the customer needs, are described below.

Students: Students are primary customers of university courses and programs. A capstone design course must be structured so as to provide students with the knowledge and skills that are necessary for them to succeed in industry or in graduate school. The course should provide a significant design experience that increases students' marketability, but that does not take so much time so as to prevent them from successfully completing other courses. Several customer needs from a student perspective are summarized as follows:

- Provide marketable skills
- Provide a significant design experience
- Require an appropriate amount of effort

Industry: Industry can be a customer of a capstone course in multiple ways. First, many capstone projects are sponsored by industry. The capstone course must provide students with the tools and guidance necessary to provide a quality product to their industrial customers. Second, since many students seek employment after graduation, industry becomes an important customer as they hire new graduates. A capstone course should assist in providing students with the skills that are valuable to industry. Providing students with marketable skills, therefore, serves the needs of both students and industry. Customer needs from an industry perspective include:

- Produce a quality product
- Produce students with marketable skills

Department: Many of the desired program outcomes for a department can be filled in a capstone course, thereby making the department an important customer of the course. In order to satisfy ABET requirements, departments often have outcomes that deal with such things as teamwork, ethics, lifelong learning, engineering economics, and understanding the impact of engineering solutions on society. A capstone course is often a good place to address some of these "difficult" program outcomes[3].

A capstone course must also be designed to work within the constraints of the department and the university. The faculty within the department will have a limited amount of time that can be dedicated to supporting capstone projects. The department will have a limited amount of funds to support capstone projects. The scheduling structure of the university will also affect the structure of the course. For example, the length of the semester, whether the university has a semester structure or a quarter structure, and other scheduling considerations will have a direct impact on project scope. At BYU-Idaho, for instance, students are admitted to the university on one of three different tracks: Fall-Winter track; Winter-Summer track; or Summer-Fall track. A capstone design experience must be made available to students on all of the three tracks. Offering a multi-semester capstone course can be difficult with such a structure since all students in a particular class may not be on the same track. Questions about whether projects should be assigned only to students on the same track, whether new multi-semester projects should begin each semester to accommodate all tracks, and other such scheduling questions must then be addressed.

Finally, the department can also act as a customer to the capstone course in cases where capstone projects are completed for the department. In such cases, the course must be structured so as to assist students in creating a quality product for the department.

The customer needs for the department can be summarized as follows:

- Meet department educational objectives
- Conform to time limitations of the faculty
- Conform to budget constraints of the department
- Conform to the scheduling structure of the university
- Provide a quality product

ABET: Although ABET may not be considered to be a direct customer of a capstone course, the requirement in criterion 4 that, "students must be prepared for engineering practice through the curriculum culminating in a major design experience…"[4] is often achieved through a capstone course. A department that is ABET accredited should have the required elements of such a design experience incorporated into their own educational outcomes. One may therefore consider that the customer need to, "meet department educational objectives" also covers the need to, "meet ABET educational objectives."

Establish Metrics

The customer needs described above are quite general and need to be defined more clearly with specific metrics. In order to provide specific metrics at this point, it becomes necessary to make some preliminary decisions about the structure and general content of the course. For example, the need to "provide marketable skills" must be defined more clearly with specific skills that the customers feel are important. This decision would ideally be made through surveys and other input from all of the customers involved and would be agreed upon within the department. For this paper, these decisions were simply made by the author to illustrate the process of applying the methodology to the design of a capstone course. The identified customer needs along with their corresponding metrics are shown in the needs-metrics matrix[2] in Figure 2.

Target values for each of the customer needs are also included in Figure 2. Again, the process of establishing target values requires that some preliminary decisions be made about the structure of the course (e.g. what is the target number of time devoted to engineering economics, etc). Target values were again determined by the author in order to illustrate the process and have not been verified by the customers.

Some of the target values can not be established at this point and must be determined through a design process. For example, what should the target be for the project sponsor? A project sponsored by industry may have pros and cons over a project sponsored by the department (it may provide the students with a more "real life" experience, but it may also require more faculty time in soliciting projects, etc.). The metrics for which target specs have not yet been established are determined through the design process that follows.

Metric	Provide marketable skills	Significant design experience	Appropriate amount of effort	Produce a quality product	Meet department objectives	Conform to faculty time limitations	Conform to the scheduling structure	Conform to budget constraints	Target (excellent)	Target (marginal)
Teamwork skills	●				●				4 Lectures; 3 Team Mtg./week	1 Lecture; Weekly Team Mtg.
Written communication skills	●				●				3 Inter. reports; 1 final report	1 Final Report
Oral communication skills	●				●				3 Presentations	1 Presentation
Design methodology	●								Full QFD; Conc. Sel.; RP	Conc. Gen; Conc. Sel.
CAE skills	●								CAD solid models; FEA	Part Drawings from CAD
Manufacturing skills	●								Design and manufacture	Design for manufacturability
Course duration		●	●						TBD	TBD
Project sponsor		●						●	TBD	TBD
Appropriate number of student hours / week			●						9-15 hrs/week	6-9 hrs/wk or 15-20 hrs/wk
Access to quality equipment				●					24 hour access to shop, equip	12 hour access to shop, equip
Access to faculty supervision / guidance				●					Weekly mtg. with faculty	Bi-weekly mtg. with faculty
Allowance for sponsor feedback				●					Weekly communication	Monthly communication
Engineering economics					●				9 lectures	3 lectures
Ethics					●				3 lectures	1 lecture
Lifelong learning					●				3 lectures	1 lecture
Required deliverables					●			●	TBD	TBD
Number of faculty involved						●			TBD	TBD
Role of faculty						●			TBD	TBD
Course structure / sequence							●		TBD	TBD
Project cost								●	TBD	TBD

Figure 2. Needs-metrics matrix for a capstone design course.

Some of the target values shown in Figure 2 would vary depending on the nature of the project (such as the frequency of communication with the customer) but the values shown are considered to be typical values for the course. A full QFD matrix was not used in this stage of the design process since other "benchmark" capstone programs may be serving different customers and have different needs. If, however, an existing capstone program could be identified which has a similar set of customer needs, then a full QFD approach could be used.

The metrics identified in Figure 2 fall into three general categories:

1. **Constraints**. These metrics are considered to be essential in order to offer the capstone course. The manner in which each constraint is implemented must be decided by the department, but the importance of each constraint is clear. The constraints include the following:
    - Access to faculty supervision / guidance
    - Access to quality equipment
    - Appropriate number of student hours per week
2. **Pre-Selected Course Content**. These metrics describe elements of the course which have already been selected as a result of populating the needs-metrics matrix. For example, several specific marketable skills were identified as important elements in the course. The process of identifying such specific metrics to fill a customer need represents a type of "pre-selection" of some of the course content. These "pre-selected course content" metrics include the following:
    - Teamwork skills
    - Written communication skills
    - Oral communication skills
    - Design methodology
    - CAD skills
    - Manufacturing skills
    - Engineering economics
    - Ethics
    - Lifelong learning
    - Allowance for sponsor feedback
3. **Design Variables**. These metrics represent variables that still need to be selected in order to determine the final structure of the course. The design variables include the following metrics:
    - Course duration
    - Project sponsor
    - Required deliverables
    - Number of faculty involved
    - Role of faculty
    - Course structure / sequence
    - Project cost

Generate Concepts

Since the design variables are the only metrics that still need to be decided on, those are the metrics for which concepts must be generated. An excellent source of ideas for these metrics includes surveys and literature reviews of capstone courses throughout the country, including Todd, et. al[5], and Dutson, et. al[6]. The survey and literature review presented in these articles summarize approaches taken in creating capstone courses at many different universities.

Several design concepts for individual design variables are summarized in the morphological matrix (see Ullman[7]) shown in Table 1.

Table 1. Morphological Matrix for Capstone Course Design Variables.

Design Variables	Design Concept 1	Design Concept 2	Design Concept 3	Design Concept 4
Course duration	1 semester	2 semester	3 semester	4 semester
Project sponsor	Industry	Department	Student	Non-profit
Required deliverables	Paper design w/ detail drawings	Prototype	Production Sample	
Number of faculty involved	1-2	25 %	50 %	100 %
Role of faculty	Consulant (Infrequent contact)	Coach (weekly contact)	Instructor (multiple contacts per week)	
Course structure / sequence	1-semester project	1-semester design course + 1-semester project	2-semester project (back to back semesters)	1-semester design course + 2-semester project
Project cost	< $500	$500 - $3,000	$3,000 - $10,000	> $10,000

The design concepts in the morphological matrix can now be combined in various ways to produce overall product concepts. Three possible product concepts are shown in Table 2. Of course many other combinations are possible.

Concept Selection

Product concepts can now be evaluated with a concept scoring matrix[2]. Each product concept is evaluated on a scale from 1 to 5 relative to the original customer needs. Each customer need is given a relative weighting which indicates the importance of that requirement. The results of the scoring matrix are shown in Table 3.

Table 2. Product Concepts

Design Variables	Product Concept A (Keep it Simple)	Product Concept B (Middle of Road)	Product Concept C (Heavy Duty)
Course duration	1 semester	1 or 2 semesters	2 or 3 semesters
Project sponsor	Student or Department	Department, Industry, or Non-Profit	Industry
Required deliverables	Paper design w/ detail drawings	Prototype	Production Sample
Number of faculty involved	1-2	50%	100%
Role of faculty	Consulant (Infrequent contact)	(1-2 as instructors, others as consultants)	(1-2 as instructors, others as coaches)
Course structure / sequence	1-semester project	1-semester design course + 1-semester project	1-semester design course + 2-semester project
Project cost	< $500	$500 - $3,000	> $10,000

Table 3. Scoring Matrix

		A (Keep it Simple)		B (Middle of Road)		C (Heavy Duty)	
Customer Needs	**Weight**	**Score**	**Wtd. Score**	**Score**	**Wtd. Score**	**Score**	**Wtd. Score**
Provide marketable skills	10 %	3	0.3	4	0.4	5	0.5
Significant design experience	20 %	2	0.4	4	0.8	5	1
Appropriate amount of effort	10 %	2	0.2	4	0.4	4	0.4
Produce a quality product	10 %	3	0.3	4	0.4	5	0.5
Meet department objectives	20 %	3	0.6	5	1	5	1
Conform to faculty time limitations	10 %	5	0.5	4	0.4	3	0.3
Conform to the scheduling structure	15 %	5	0.75	5	0.75	2	0.3
Conform to budget constraints	10 %	5	0.5	4	0.4	2	0.2
	Total	3.55		4.55		4.2	

It can be seen from the decision matrix that product concept B received the highest weighted score. In general, concept A was viewed as not providing as significant of a design experience for the students, although it easily conforms to budgeting and scheduling constraints. Concept C was viewed as providing a very strong design experience for the students, but was more difficult to keep within budgeting and scheduling constraints. For the unique case at BYU-Idaho in which students are admitted to one of three tracks, concept C presents significant challenges with regard to scheduling since not all students in a particular class may be on the same track. Concept C therefore received a low score for conforming to the scheduling structure.

In the final analysis, the value of the scoring matrix is not in the final weighted number for each concept, but rather in the process of arriving at a consensus among the faculty as to what elements are the most critical for the course. The scoring matrix forces the faculty to evaluate specific elements of the course and provides a justification for the final structure of the course.

As the design process is often iterative, the final form of the course may turn out to be a combination or alteration of the original product concepts. The current structure of the capstone course at BYU-Idaho is something of a hybrid between concept B and concept C. The course is structured as a sequence of courses that do not need to be taken back-to-back (thus accommodating the 3-track admission structure of the university). The first course in the sequence is a design methodology course. The second course in the sequence is where the actual capstone project is completed. A third elective course is available for those students who choose to complete a more extensive project that requires more than a single semester to complete. Projects for the course have been sponsored by industry, the department, and individual students, although the goal is to have a significant percentage of the projects come from industry. Faculty involvement has been limited primarily to two lead faculty members. The design process described in this paper indicates that faculty involvement should be spread out to a larger portion of the faculty who could serve as consultants or coaches to student teams.

Conclusions

The application of a structured design methodology was proposed as a means of designing (or of reviewing and revising) a senior capstone design course. The structured design methodology forces the faculty to identify specific customer needs that should be filled in the course and provides an opportunity to explore different options for filling those needs. The result of applying this process to the review of the capstone course at BYU-Idaho indicated that the current structure of the course meets customer needs quite well, but the role of the faculty could be changed to improve the course. Specific feedback from customers (students and industry) relative to the various aspects of the course has not yet been obtained.

Although departments at other universities may identify different customer needs, establish different metrics, and assign different weighting values to the various elements of the course, the process illustrated in this paper should be applicable to a wide range of departments and courses.

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