2006-1543: INTRODUCING ‘TOTAL DESIGN’ IN AN ENGINEERING DESIGN CURRICULUM: A PILOT EXPERIENCE

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Introducing ‘Total Design’ in an Engineering Design Course: A Pilot Experience

Introduction

During the past ten years, most engineering schools have introduced new engineering design courses or enhanced existing courses in their undergraduate programs. This curricular evolution had its origins in the widespread perception amongst engineering professionals that engineering education had become overly analytic and science-based, detached from its societal milieu and purpose, and that, as a result, engineering students were not adequately prepared to engage in engineering practice upon graduation. Particular efforts were devoted to the introduction of first-semester design courses in order to engage students’ enthusiasm for engineering from the very beginning of the program. Pre- and post-changes data have supported the impact of introducing innovative design processes in the Freshman Year. The “design spine,” a series of eight courses with one given each semester, was introduced in the engineering curriculum at Stevens in 1997. Under the current curriculum, which was revised in 2004, the first and second courses of the design spine do not have a disciplinary focus whereas the succeeding courses are associated with engineering science courses (Design III to V) or the student’s capstone design, which may include multidisciplinary projects (Design VI to VIII).

In this paper the authors report on a pilot experience to design, develop, and implement changes to the first course of the design spine (Design I or E121), aimed at introducing the first elements of a comprehensive approach rooted in “Total Design,” with implementation of other elements in other courses to follow. Total design is the systematic activity necessary, from the identification of the market/user need, to the selling of the successful product to satisfy that need – an activity that encompasses product, process, people and organization.

Rationale for Total Design

Engineering education is, by necessity, mostly concerned with the acquisition of knowledge (in the humanities, management, the sciences...) and analytical techniques and skills in engineering, usually within a specific discipline or domain (e.g. mechanical, electrical, etc...). The rigorous application of such skills and knowledge to engineering elements is usually called partial design, and is often exemplified in some senior capstone design projects. But in today’s world, industry is concerned with total design: the integration of numerous technical and non-technical disciplines toward the development of new products, systems and services. In this regard, a misdirected engineering rigor, overtly focused on a discipline, will always give rise to sub-optimal total design. Furthermore, and this is a major factor when considering multidisciplinary design projects, each student should be able to see how his partial contributions fit into the whole. Success in the market place requires total design rigor and engineering rigor of the highest order – never the one without the other.

Increasingly, we are realizing the challenges of teaching engineering design to our students so that they will be ready to practice in a global socio-economic environment increasingly dominated by engineering systems and the design of engineering systems, and driven by innovation. Students should be exposed and, thus, should be able apply the concepts and methodologies of total design in order to be able to effectively participate on such multidisciplinary teams. For example, students should learn how to define problems in response to a
need or a technological opportunity, determine customer or stakeholder requirements, formulate alternative concepts and select an optimal one, etc. Engineering students often seek the “best” solution (which to them is a purely technological one and most often entirely rooted in a specific engineering discipline) with little regard for the context in which their product, system, or service may be deployed, the societal or business need it may fulfill or even its relations to all the other engineering, business or even artistic domains contributing to the successful introduction of any new product or system. This design approach restricts the ability of students to identify and resolve errors through the different life-cycle phases, therefore, resulting in most errors getting caught at the very downstream phase of systems integration – when the entire system is being assembled and tested for the first time. A further drawback of this methodology is that the students are not able to establish and trace the functionality of the system throughout the life-cycle resulting in the need for rework.

Engineering curricula are necessarily concerned with specific engineering information, techniques and technology which lead them and their teachers to practice partial design, as reflected by the organization of engineering schools into specialized departments. In order to address the above challenges, total design should be taught and practiced in a progressive manner, with enhanced information, knowledge and techniques leading to increased rigor in a total design sense, and incorporating engineering rigor. Similar concerns have been experienced and voiced by engineering faculty at other institutions.10, 11

Engineering Design Course Objectives

Our overarching vision is to enable students to see the “whole” picture of the design process, in the top-down approach of system design and the bottoms-up approach of partial design which they will learn mostly from upper-level disciplinary courses.

1. Students will not only learn and apply general methods related to the ‘content’ of multidisciplinary engineering design but also how design is practiced in a ‘context’. Content is embedded within context. The content is normally emphasized as the essence of engineering design (as partial design or detail design) because it includes the steps and processes involved in carrying out an actual physical design. This is true especially beyond the sophomore year when the design projects are often (and perhaps, unfortunately) rooted within a single discipline. The context is the world out of which the need for the design arises in the first place and in which the implemented design will eventually function.12

2. Students will be able to develop a common view of the design process and therefore, subscribe to a common methodology with a minimum of misconceptions. This goal can be met if students engage in multidisciplinary design projects in terms II and III, practice true system design and appreciate how different partial designs are integrated into a whole.

3. Students will use systems thinking in the engineering design process. Systems thinking, a process of defining a phenomenon holistically – by its contents, objectives, interactions, relationships, and environment – is integral to the design process. It uses the common tools of analysis and synthesis to form new conclusions.13
4. The preceding goals essentially address the development of higher thinking skills in young adults (analysis, synthesis and evaluation in Bloom’s taxonomy) and consequently will pose very challenging questions regarding the design and implementation of an assessment system for the evaluation of learning outcomes. Our final goal is then for the faculty to develop and implement appropriate methods that promote the realization of goals 1-3 and to study their impact on student learning and holistic thinking.

**Engineering Design Course Implementation**

Key elements of the current design course have been preserved and these include the usual aspects of communication skills, teaming, project management, presentation skills, and design applications involving working drawings, some design analysis, machine shop exercises, etc. After doing the reverse engineering of an electric screwdriver, the students work on a semester-long project that involves the design, development, and testing of an autonomous robotic car with all the associated detail design. Design I is integrated with other concurrent engineering courses such as Engineering Graphics and Introduction to Computers. The course instructors are adjunct faculty drawn from industry and consulting firms. Each instructor is or has been a practicing design professional.

Materials for students were developed during the Summer of 2005 and the new revised course was given in the Fall of 2005. Nearly all the educational materials developed are modular, Web-based and largely in a stand-alone format to facilitate dissemination to diverse groups. Additional and comprehensive materials were created for the course instructors, who also attended a workshop prior to teaching the course.

Both total design and system design have the same premise: that design is an activity whose starting point or trigger is a societal need or business opportunity that may arise because of a functional or operational deficiency, a technology fusion or breakthrough, behavior analysis or an accidental discovery. The major aim of systems engineering is to develop an operational model of the system for all phases of the life-cycle, the model is then used as a basis for detail design. It is this top-down approach to design that has been missing from engineering curricula and that will be increasingly needed in the design of future systems. In fact, total design encompasses most of the approaches, methods and tools of system design and systems engineering as shown in Figure 1.
A more detailed overview and linkages of the total design process appears in Figure 2. Each phase in the life cycle of a product, system or service, as shown in the side bars would include essentially the same ten steps. As a result 10 modules were developed for Engineering Design I and II. Only the first four modules have been implemented in Design I so far and used as examples for the screwdriver reverse engineering and the design of the robotic car. These include:

1. Need and Market Opportunity
2. Stakeholder Identification, Requirements Gathering and Analysis
3. Concepts Generation, Evaluation and Selection
4. Operational Scenarios
All the design modules are developed with short presentations by instructors which are followed by class exercises and hands-on-projects in order not to disrupt the lab-based environment and experience of Design I. The modules address the concepts, tools, and methods of system design in a progressive manner. This project-based or problem-based approach enables students to move towards a deep approach, and promotes cooperative learning and active learning. All the modules include in class assignments to develop items 1-4 above in the case of a portable audio player, an ATM (Automatic Teller Machine), and an electric screwdriver. The same items are the subject of assignments for the robotic car. The concepts addressed in each module are:

**Need and Market Opportunity**
- Problem definition
- Identification of opportunities
- Systems Thinking

**Stakeholder Identification, Requirements Gathering and Analysis**
- Identification of direct and indirect stakeholders
- Context of the system
- Stakeholder requirements gathering
- Translation of stakeholder requirements into design requirements (using a simple form of TQM)

**Concepts Generation, Evaluation and Selection**
- Need for conceptual design
- Development of conceptual designs
- Comparison of suitability of the alternative concepts (Pugh matrices, TQM and other methods would be used by the students)

**Operational Scenarios**
- Need to understand the operating scenarios of the system
- Identification of various operating scenarios
- Understand and communicate the identified operating scenarios (Swim lane diagrams and Use cases would be used by the students)

**Course Assessment**

The implementation of the novel elements of the course as discussed above has been assessed by two different methods with different objectives. The course performance criteria addresses the student’s understanding of total design, the ability to identify need or market opportunity, the ability to identify stakeholders, the ability to gather and analyze the requirements, and the ability to perform conceptual design. The other method of assessment, for which the results are not yet available and for which a multi-year effort is envisioned, uses the Input/Experience/Output (I.E.O) model\(^\text{16}\) to understand and improve student learning. The course outcomes that are proposed to be measured with this model are the student’s reach and fit in the curriculum, increases in student engagement, increases in student satisfaction, increase in performance (grade curve) in other design courses, etc...

While revising Design I (E121) special consideration was given to the fact that the materials developed were consistent with and supported the ABET criteria described below. The intent was that the students adopt imaginative and innovative approaches to the design process and establish a complete design.

1. To design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.
2. To function on multi-disciplinary teams.
3. To identify, formulate, and solve engineering problems.
4. To understand the impact of engineering solutions in a global, economic, environmental, and societal context, and
5. To use the techniques, skills, and modern engineering tools necessary for engineering practice.

The assessment of the effectiveness of the novel elements in Design I was conducted by means of survey at the end of the course. A Likert scale from 1 to 5 was used. There were 16 sections of Engineering Design I offered in Fall 2005. The total number of students enrolled in the course was 346 and the survey response rate was 42% (145 students). While designing our course survey questions, we made sure that the course objectives discussed earlier were being addressed. The survey questions are listed below:

- **A-1.** You are able to understand that product design is a combination of many technical and non technical disciplines.
A-2. During a product design, you are able to consider all aspects of the product from the start of its design through final disposal at the end of its useful life.

A-3. You are able to identify direct and indirect stakeholders (including payee, customer, and user) and their requirements for a product.

A-4. You are able to write stakeholder requirements in the form of subject + verb + modifier and quantify the need in measurable terms.

A-5. You are able to write stakeholder requirements without specifying a solution or selecting a particular design alternative.

A-6. You are able to come up with alternative design concepts.

A-7. You are able to understand and evaluate the alternative design concepts based on important and relevant criteria.

The results for the survey questions, A-1 to A-7 are shown in Table 1. The survey was supplemented by students’ comments which are also used in the brief discussion below.

### Table 1 Survey Results (A-1 to A-7)

<table>
<thead>
<tr>
<th>Course Evaluation For E121 - Engineering Design 1</th>
<th>(1 is Strongly Disagree; 5 is Strongly Agree)</th>
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<td>Question</td>
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<tr>
<td>A-1</td>
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<td>A-7</td>
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The results indicate that the students seem to have an understanding of the multi-disciplinary aspects of product design and this factor may be attributed also to the variety of projects to which they were exposed. The students seem to have developed an understanding that conceptual design, including concept generation and concept evaluation, is important (even though some of them reverted to the usual trial-and-error approach for some elements of the car project). Students’ learning experience with the identification of stakeholders and stakeholder requirements varied. While most of the students reported agreement on having learned these concepts, the responses were not as good as on other questions. Many students associated stakeholders only to customers and users- and this can be attributed to three factors: a) more interactive class exercises need to be developed that can help the students understand the concept of stakeholders and requirements better, b) the technical terms used in system design have to be simplified to make the students observe, analyze and use the concepts in their design, c) the attention span of students for in-class lectures is reduced in a lab environment. Students also experienced difficulties in translating stakeholder requirements into design requirements. To this end, case studies, illustrative examples and project walk-through should be added to the (shorter) lectures.

**Conclusions**
In the revision of the first course (Design I) of the design spine, our focus has been on the early stages of development of product, system, or service starting with market and user needs or technological opportunities. In other words, formulating stakeholders and customer needs and translating them into a product design specification, and determining and examining various conceptual design alternatives. These elements will be repeated in Design II, the follow-up course, within a multidisciplinary perspective, as a prelude to determining the functional architecture and the physical architecture in order to develop a functional view of the product, for all stages of the product lifecycle, from cradle to retirement. Groups of students will then engage in more focused activities, which will enable them to be exposed to and explore various disciplines, since they do not select a major until the third semester. Students will thus see the “whole” picture of the design process, in the top-down approach of system design, and the bottom-up approach of partial design. Students will develop a common view of the design process early and therefore, when engaged in partial design activities later on in their studies, within their discipline or in a multidisciplinary team, subscribe to a common methodology with a minimum of misconceptions – leading them to practice true system design and learning how different partial designs are integrated into a whole.

One of the lesson learned that can be generalized for application in similar courses and programs is the preparedness of the teaching instructors especially those who are adjuncts. In our case, the instructors were unanimous of the view that the improvements to the course were ‘extremely relevant and important’. However, they needed more time to familiarize themselves with the new materials. Therefore, in a way, our approach to implement the changes in a modular format was appropriate as it allowed incremental implementation of the materials.

The future work will include the next phase of implementation and improvement of the total design modules across the remaining seven design courses. Continued implementation of the total design methodology across the “design spine” would involve addressing the challenges such as disciplinary focus of the remaining successive design courses and their association with other courses.

Acknowledgements

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References

16. Center for Effective University Teaching and GE Master Teachers’ Team, “Using Classroom Assessment Date to Improve Student Learning”, Northeastern University, 2000-2001