Using Mastery Learning to Teach the Engineering Design Process

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Abstract

Capstone design courses are often used to teach the engineering design process. Typically, students have one opportunity to experience the design process before graduating as qualified engineers. The Design Trilogy is a capstone design “course” consisting of three stand-alone courses completed in consecutive years. In Design Trilogy I, students find a conceptual solution to a problem provided by an industry client. In Design Trilogy II, students are expected to reach the analysis stage while working on a new industry problem. Finally, Design Trilogy III students are expected to produce a detailed design, including a cost analysis and prototype (if possible), for a third industry problem. Thus, students have a better opportunity to master the engineering design process because they have three exposures to the early stages of the process.

Keywords: *capstone design, mastery learning, engineering design process, engineering design education*

1. Introduction

Upon graduation, engineers are expected to know how to “design”. This creative and analytical process is what distinguishes engineering from other professions. But, how does one learn how to design?

Is it a process that can be learned from a textbook? Can an engineering professor provide an adequate explanation of the process during a lecture? There are books that describe various models of the design process and many of us have attempted to explain the process during lectures, but it has long been recognized that students must somehow experience the design process. It is for this reason that capstone design courses have been created.

The original concept behind a capstone design course is that, before graduation, students should be given an opportunity to use the technical knowledge they have gained to solve a design problem. In some cases, the professor may construct a problem scenario; in other cases, actual industry problems are used. Regardless of which model is used, the expectation is that students will begin to behave as design engineers. They will study the initial problem statement to identify what is really needed. They will identify relevant constraints and limitations. They will generate a number of possible conceptual solutions that warrant further investigation. Using analysis techniques learned during previous classes, they will select the “best” solution. The details of the “best” solution will be finalized and the solution will be communicated to the client. In a nutshell, this is the engineering design process.

Although the design process can be described in five short sentences, it is not a simple process. Is it realistic to expect students to fully appreciate the intricacies of the process over the course of three

months when it is only one of many courses being taken simultaneously? Undergraduate students often do not have the opportunity to sit back and reflect upon what is being done; they are too busy studying and completing assignments. It is our contention, therefore, that it is not reasonable to expect students to fully understand the design process from a one-term capstone design class.

As an alternative to a one-term capstone design class, we have introduced three, one-term classes (which have come to be known as our “Design Trilogy”) that students must complete sequentially. In each class, students have the opportunity to work on a design problem provided by industry. In the first class, which is usually taken by students in the second year of the undergraduate engineering program, the expectation is that individual students will begin to learn how to function as a design team and will produce a conceptual solution to the problem. In the subsequent years, as they progress further into their undergraduate program, it is expected that solutions can be analyzed according to the other engineering classes that have been completed. The Design Trilogy, therefore, utilizes “mastery learning” because students have three opportunities to experience the design process. It is anticipated that students will gain a better understanding of the overall design process, particularly the early steps of the process, through the completion of three design projects. With a year between the completion of each step in the Design Trilogy, students have adequate time to reflect upon the previous year’s project. This also contributes to a better understanding of the design process.

The other unique aspect of the Design Trilogy is that technical communication instruction by a non-engineer has been integrated into each of the three classes [1]. As identified earlier, communication of the design solution to the client is the final step of the design process. Communication, whether by spoken word, written word, or picture is critical to the success of the design process. This truth has long been recognized by engineering educators and is the reason why “technical communications” courses exist in engineering curricula. Unfortunately, engineering students seldom recognize the importance of technical communication skills. The perceived lack of importance for communication skills has been emphasized by the stand-alone course in technical communications. Integration of technical communications instruction with teaching of the design process has given students an opportunity to see the relevance of communication skills to the success of the design process. Students are motivated to do a good job of communicating their ideas because

they know that they are working for an industry client, potentially a future employer!

This paper gives an introduction to the Design Trilogy that has been developed in the Department of Biosystems Engineering at the University of Manitoba. Our experiment with the Design Trilogy began in 1998, and we have been striving to improve it each year since then. Formal integration of technical communication instruction occurred in 2003. We have learned a lot about teaching design and we have made many improvements, but we have not yet run out of ideas for further improvement. Being involved with the Design Trilogy has been both exciting and rewarding. We think of it as our own design project that must be completed each year.

2. The biosystems engineering Design Trilogy

For engineering educators, the term “capstone” design has become a well-recognized term. A capstone course is one in which the students are expected to apply knowledge gained throughout their education to a real-world problem. A capstone design course has been part of the curriculum in the Department of Biosystems (formerly Agricultural) Engineering at the University of Manitoba for several decades.

In recent years, engineering educators began to realize that graduating engineers may not fully understand the process used by practicing engineers to design an object. What has come to be known as the “Design Trilogy” at the University of Manitoba is a sequence of three required courses that attempt to teach the design process. These three courses comprise our version of a capstone course.

3. Philosophy of the Design Trilogy

The Design Trilogy was developed based on the philosophy that students should have the opportunity to apply their developing engineering skills under conditions that are similar to those they can expect to work in following graduation. By using industry-based projects as the core of each of the three courses, and having the student teams function as consultants to those industries, this “real world” environment can be simulated reasonably well.

Prerequisite to the Design Trilogy is a first-year *Engineering Design* course where engineering students learn to work in teams on open-ended projects. Significant effort is advanced to make students comfortable with team building and idea

creation. The Design Trilogy allows students to build on that base while experiencing a level of design responsibility that increases as their technical and analytical skills are developed.

Design is more than the application of technology. Communication, accountability, time management and project planning are all critical skills that students must develop. Expectations increase as students proceed through the three courses. In the initial course, the design projects are concept oriented. By the time students reach the third course, however, a much greater level of detail is required. Requirements to meet with their “clients” and to provide minutes for those meetings assures that the time and money constraints within industry become a part of the students’ learning process. Company-imposed constraints, not always visible to the outsider, become critical elements to be considered in the design process.

4. Learning objectives of the Design Trilogy

The overall objective of the Design Trilogy is to teach undergraduate engineering students the entire design process from formulation of the design problem to fabrication of a prototype. Within this overall objective, the following specific objectives have been set: i) to strengthen team building skills; ii) to strengthen communication skills (all aspects); iii) to instill a sense of professionalism; iv) to develop project and business management skills, and v) to instill safety and human factors engineering principles.

Our intention is not to simply expose undergraduate students to a design environment. This could be achieved by encouraging participation in a co-operative education program. Rather, we intended to create an environment in which we could teach the design process within the context of real design problems. It was decided that three, thirteen-week semesters would be required to provide enough time for the students to fully absorb the experience. The fall term, four-credit courses are offered at the second, third, and fourth-year levels. During second year, students develop a conceptual design in response to a problem submitted by industry. During third year, students provide a detailed design (complete with engineering drawings and analysis) in response to a problem submitted by industry. Finally, in fourth year, students provide a final design (complete with an economic analysis and an in-depth engineering analysis) in response to a problem submitted by industry.

Using this model, more is expected from design teams according to their year of registration. With practice, the students should become more efficient at completing the preliminary stages of design. This is an example of mastery learning where students are able to repeat previously learned tasks so that they can learn from their shortcomings of the previous experience. As a bonus, this model allows each undergraduate student to work on three different design projects within three different design teams during their engineering education.

5. Lecture content in the Design Trilogy

Design Trilogy I is the first component of the Biosystems Engineering Design Trilogy. Students typically register for this course when they first enter the Biosystems Engineering department. Thus, this course has been chosen to give students an overall understanding of Biosystems Engineering, past and present, and how it fits into engineering, agriculture, biology-based industry, and the professional world in general. It provides a team-based conceptual design experience, which illustrates both the design process and the need for further study in both technical and non-technical fields. The issue of safety in design and in the engineering workplace is introduced.

Related to the design projects that are completed, lecture material also covers an introduction to project management issues (i.e., project control, scheduling, and monitoring), engineering business issues (i.e., budgeting, costing of engineering work), and techniques for communication of engineering work (both written and oral).

Design Trilogy II is the second component of the trilogy of design courses in Biosystems Engineering. Typically, the course is taken by third-year students who are at the mid-point of their engineering education. From their previous experience with Design Trilogy I they know how to generate a conceptual solution to a problem, but they lack experience in the analysis of a conceptual solution. Will the idea work? How will the user interact with the device? Is it safe? Answers to such questions are critical to the success of a design.

Because issues of safety engineering and human factors engineering are not addressed anywhere else in the Biosystems Engineering curriculum, it was felt that Design Trilogy II was a good fit as students learn how to critically analyze a conceptual solution. General principles of both safety engineering and human factors engineering are covered to give students a sense of the issues that must be considered. Case studies of engineering failures are used to illustrate the consequences of neglecting consideration

of the human being in the human-machine interaction. Students seem particularly interested in this content because it links the technical information that they have learned in other courses with their sense of societal responsibility that has led them to a career in engineering.

Typically, students in Design Trilogy III are in their final year of studies in Biosystems Engineering. By the time students are in Design III they have encountered a broad range of coursework. The intent of this course is to provide an opportunity to apply theoretical knowledge to an actual industry-based design problem in order that they “make connections” between otherwise discrete course material. All too often survival to graduation understandably becomes a paramount objective for engineering students with heavy course loads. Unless linkages between various engineering courses are made apparent by instructors, this process does not necessarily happen with the students themselves. Design Trilogy III is comprised of three principal components; lectures, an industry-based design project and hands-on labs. By the end of a 13-week term the overall objective of the course is to provide students with a design experience that requires them to synthesize theoretical knowledge, hands-on experience, and interpersonal skills to produce a design solution for a current industry-based problem. The course provides a blend of object-oriented and people-oriented opportunities for the students.

Given that the main focus of the course is to provide a “design experience”, the emphasis on formal lectures is reduced when compared with traditional engineering courses. Regardless of the path students may take upon graduation it is safe to say that they will all be involved with business in some fashion. With this in mind the early portion of the course is shaped around being an engineer within a consulting business. To get things started students are asked up front, “How much is your time worth?” This simple question never fails to stimulate discussion. It provides a springboard to explore and debate such things as an engineer’s role and responsibilities in society, professionalism, ethics, and liability in engineering practice. A portion of the lecture time during the term is used to discuss issues that may be arising within group design projects. In an informal fashion students present design challenges they are facing within their project for discussion with the larger class. Often, a formal lecture is only a portion of regular 50-min class with the remainder of a class used to give students time to work with their group. During these classes the instructor meets with each group to monitor progress and facilitate discussion when required or requested. The role of the instructor is not to direct the design process, but to facilitate it within the time-frame of a

13-week term. Each group must be allowed to define the design problem, explore their options and then put a focus on their direction. Intervention on the part of the instructor is related predominantly with assisting a group to find focus. Since projects vary from year to year, one could say that every time this course is given, it is a design exercise for the instructor as well.

6. Industry-based design projects in the Design Trilogy

The focal point for each course of the Design Trilogy is the industry-based design project. This tends to be the aspect that identifies the Design Trilogy as being unique. Design projects are completed by students enrolled in all three courses of the Design Trilogy. Industry design problems are identified by the project coordinator for the U of M IDEA Program (a program funded by the NSERC (Natural Sciences and Engineering Research Council of Canada) Design Chair in the Faculty of Engineering at the University of Manitoba). The project coordinator establishes contact with industry in the province and solicits project proposals. Selection of appropriate project proposals is completed in consultation with the instructors of the Design Trilogy. Industry cooperators pay a differential fee of \$500, \$750, or \$1000 for projects that will be worked on by Design Trilogy I, Design Trilogy II, and Design Trilogy III students, respectively.

Within the first two weeks of the course, industrial clients present design projects to the students in each course. Each student submits a one-page proposal ranking their choice of project, stating why they want to work on their first choice and any relevant skills they may bring to the project team. Design teams are then determined by the instructor based on a review of the proposals. Whenever possible, students are given their first choice. This is dependent upon class size, projects that students have worked on in past Design Trilogy courses, and maintaining a balance of group size.

Once established, each team is required to determine a company name. From that point on, all correspondence with the instructor and industrial client must be done using the company identity. For Design Trilogy III, each team submits a proposal for engineering services stating what their fees will be for the project. This is submitted to the instructor only. During the term each design team tracks their individual time and group meeting time. At the end of the term the original proposal is compared with a total of actual time and typical charge-out rates. This has

been viewed by students as an eye-opener, as time input is typically underestimated.

During the term, design teams meet with their industry client and with the instructor. Since student schedules are generally full, it is important to provide adequate time. To that end some of the lecture time is given over to project meetings and, with approval of the instructor, some labs may be used for off-campus meetings with industry clients. Given the complexity of the projects it was not realistic or reasonable to expect students to conduct meetings only outside of class time.

Upon completion of the project each design team submits a report and makes a formal presentation at a CSAE (Canadian Society of Agricultural Engineering)-sanctioned meeting off-campus. A copy of the written report is also submitted to the industry client.

7. Hands-on labs in the Design Trilogy

The hands-on laboratory component of Design Trilogy I is limited to an activity of “reverse engineering.” Students, working in pairs, are given a mechanical device consisting of 15-25 parts. The device is disassembled with careful attention to the steps required to re-assemble the device. An assembly drawing is prepared. In a subsequent laboratory period, the box of parts and the completed assembly drawing is given to a different team of students. Using the information provided in the assembly drawing, the students attempt to re-assemble the device. Each assembly drawing is peer-evaluated by the team of students using it to re-assemble the device. Not only does the activity give the students some hands-on experience using common tools in a shop setting, it also emphasizes an important component of engineering communication.

For Design Trilogy II, there is one hands-on activity that relates to the safety engineering principles discussed during the lectures: students design and manufacture a safety shield for a machine. As an example, students designed a belt shield for a garden tiller. After taking the necessary measurements from the tiller, conceptual designs were developed. A first attempt at manufacturing the shield consisted of making the shield out of bristleboard. This allowed the students to visualize their design to see whether it would actually fit together as planned. After making necessary modifications to their design, a second prototype was manufactured using sheet metal. Students were expected to do the fabrication themselves, giving them exposure to basic shop fabrication techniques and relevant safety procedures. The final test of the prototype is to install the shield

onto the tiller. Much learning occurs during this process, especially if the shield does not fit as planned.

Considered by many students as perhaps the most enjoyable component of Design Trilogy III are the hands-on labs conducted on a weekly basis. The objectives behind these labs are twofold. In some cases design teams will fabricate a model or prototype of their project. The lab introduces students to most of the equipment in the Biosystems Engineering machine shop. From a pedagogical perspective, these labs provide students with insight into the skillset required to support engineering design. In most instances engineers are dependent upon tradespeople to take their designs from the drawing board to a physical reality. Every engineer must have an appreciation for this technical know-how and the tolerances of production equipment. In the absence of this understanding, a design may not get past the concept stage. The goal of this lab is not to create tradespeople, but rather to let students experience, first-hand, various tools of production and the processes associated with them. To this end each participant experiences arc welding, oxy-acetylene cutting, sheet metal layout and forming, spot welding, soldering copper pipe, metal lathe operations, wiring, reading drawings, and wood working. A project comprised of several parts involving the above processes is completed during the term. Students are not told what the complete project is up front. They receive a drawing for a component each week. Once all components are complete they get an assembly drawing. It is at this time that many students come to appreciate the meaning of tolerance. One interesting by-product of this component of the course is that some students who are timid at the beginning often seem to have more confidence and are certainly more comfortable around the machinery by the end of the term.

8. Student evaluation in the Design Trilogy

Although the grade allocations differ from course to course, students are evaluated on both the lecture material covered in the course (using assignments, midterm examinations, or final examinations) and the design solution based on the problem presented by industry (using a written report and an oral presentation). Of particular interest is the method used to evaluate the written reports to ensure that “social loafers” are identified. First, course instructors evaluate the design reports according to a rubric, yielding a team grade. A peer evaluation process is then used where students have 20 points to allocate between the members of their design team (including themselves). They are instructed to distribute the

points according to their assessment of the contribution made by the various team members. The peer evaluation process is confidential. The instructor tabulates the points received by each individual. The individual's project grade is adjusted according to the number of points received. If 20 points are received, no adjustment to the team grade is applied. If more than 20 points are received (i.e., this is an indication that the student contributed more than his or her fair share to the project), the individual's project grade will be increased according to a specified formula. When less than 20 points are received, the individual's project grade is decreased. From our experiences over the past several years, this process works well to both reward those who put in extra effort and to penalize those who feel that the project is not worth their effort.

9. The on-going experiment

It has been six years since the Design Trilogy has come into existence. Thus far, no two offerings of the Trilogy have been the same. Each year, we come up with new ideas to improve the overall package. Some ideas work and become a core component of next year's version, but some ideas do not work as

envisioned on paper. We are not sure what the final version will look like, but the journey we are on right now is very rewarding!

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References

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