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PREPARING AND COORDINATING UNDERGRADUATE ENGINEERING DESIGN PROJECTS

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***Abstract*—** Design projects have become common in engineering classrooms. Earlier exposure to and training in the design engineering process hold much value for an enriched experience and an in-depth understanding of engineering design. Simultaneously, students in their earlier years require more guidance and frequent feedback to inform their own expectations of learning objectives, as well as develop effective learning strategies. In this paper, we will examine the considerations required to design and conduct an undergraduate engineering design course, with reflections from several years' experience with a second-year mechanical engineering design course.

Keywords- Design; Experiential Learning; Problem Based Learning; Collaborative Learning; Course Creation

I. INTRODUCTION

Design is the primary mode in which professional engineers operate, but until recently, there has not been a focus on teaching design and the associated soft skills. This has led to decades of engineering graduates that are excellent scientists, but lack design, analysis and professional skills [1-4]. Surveys of industry professionals and recent engineering graduates show that the attributes of design, teamwork, communication and problem solving are the most important in their daily work [3][5][6]. There have been efforts to improve these skills in undergraduate programs, beginning with the introduction of Capstone Design courses, and later, cornerstone design courses to give first year students an introduction to the design process.

This paper describes the process behind the development and coordination of a second-year mechanical engineering design project course with the goal of creating a bridge between the first year introduction to the engineering design process, and the more complex, open-ended Capstone Design projects.

Cornerstone Design courses have been introduced relatively recently and were created in response to the apparent disconnect that first and second year engineering students were feeling from engineering practice [4]. The outcomes from these Cornerstone Design courses can vary greatly depending on the constraints placed upon the course, such as available time, resources and class size. Additionally, the prior knowledge and training of first year students can vary greatly, limiting the potential subject matter and scale of the projects. Despite these limitations, Cornerstone Design courses have had great success, and their introduction has helped to increase student satisfaction with their early education [4].

II. BACKGROUND

A. *Experiential Learning*

Kolb's experiential learning cycle [7] is the model that is most commonly associated with teaching engineering design and the engineering design process. Kolb's cycle is composed of experimentation, concrete experience, reflective observation and abstract conceptualization. The iterative nature of this learning theory matches well with the engineering design process as a whole, where a product is designed, built, tested and analyzed, and lastly reflected upon for possible future design improvement. The experiential learning cycle can also be applied at a smaller scale to the individual steps of the design process. For example, during the conceptual design phase, students will generate potential concepts, evaluate the concept against design goals and criteria, and use this knowledge to iterate their designs if they do not satisfactorily meet their requirements.

Kolb's experiential learning cycle has been implemented into several pedagogical methods. Of interest when discussing engineering design projects are Problem or Project-Based Learning (PBL) and Cooperative Learning (CL). PBL is a student focused approach to aimed at improving the problem-solving skills of students. Students are encouraged to hypothesize solution methodologies and perform independent research to solve problems. Students then propose solutions, and test their appropriateness, followed by critical reflection on the process. Teachers act as facilitators to the process [8]. Cooperative Learning is a teaching methodology focused on improving how students work in teams, which is a very important part of design project experience. The most commonly implemented model of CL is that of Johnson et al. [9], which specifies 5 basic conditions under which students must work; positive interdependence, individual accountability, face-to-face promotive interaction, appropriate use of collaborative skills and regular self-assessment of group functioning. Research has shown that students taught in this method tend to have higher individual academic achievement and improvements in design skills, communication skills and group skills [10].

B. Design Project Selection

Choosing the correct subject for an engineering design project, particularly for first or second year students, can be difficult. The project should be challenging, pushing them the think beyond what they have seen in class. The project should be scoped in a way that is able to be completed within the timeline set by the course. The subject of the project should be well understood and documented and not include material from the fringes of scientific understanding. As these projects are part of an engineering education, they should emphasize the application of theory (mechanics, thermodynamics, etc). Finally, they should use the engineering design process as a framework.

Dutson et. al. [11] identified five potential sources for design projects for use in engineering curriculums. In hypothetical projects, course directors invent a project which can be tailored to meet the requirements of the class. Student selected projects, in which students, sometimes with guidance, choose the problem they wish to solve. Research related projects are recruited from professors and related to their research activities. Finally, industry sponsored projects are solicited from industry, ideally to solve real problems a company faces.

Each of these sources for design projects has their own advantages and disadvantages depending on the desired outcomes of the project, and each has been applied to Capstone projects. When working with Cornerstone design projects however, meeting the requirements of “understood subject matter” and “application of theory” is significantly more limiting. Searching for design projects from research, industry or student design competitions that can meet the scope requirements as well as contain only the theory and skills that first or second year students have been exposed to would be extremely difficult. Student selected projects are also difficult if the course developer would like to include the full design cycle (design, build and test) as students at that stage of their education have a poor understanding of the full scope of work required for projects. Hypothetical projects are the most convenient choice for project topics as all aspects of the scope, technical requirements and resources required can be tailored to meet the needs of the course. If properly contextualized, a hypothetical project can teach many of the same lessons as a “real” engineering problem.

C. Teamwork

Teamwork is often cited as the most desired outcome from team projects [12]. Teamwork is the primary mode in which professional engineers operate and encouraging students to work well within a diverse team environment is of great interest for course developers. There are many models of effective teams that have been introduced [13-15], and there are several key behaviors that each of them attempts to promote.

The first behavior encouraged is interdependence [12]. In order for an effective group to complete their task they must rely upon on the work of the individual members of the team; if one member of the team does not complete their assigned task, it prevents the entire group from completing the project. There are varying levels of interdependence that teams can operate under from pooled interdependence to intensive interdependence. In pooled interdependence, students divide tasks, and complete them in parallel often with poor levels of communication. Intensive interdependence is considered the more desirable form, and each of the team members’ divided work relies upon input from other team members’ work, which encourages communication and coordination.

Trust is another important factor for effective teams. Trust itself can be defined in many ways, but the definitions most closely related to team effectiveness is the students’ confidence in the abilities and trustworthy intentions of their team members [12]. Trust can be encouraged in teams through team-building exercises that help to reveal the abilities and strengths of the team members, as well as share past teamwork experiences.

The most cited and common complaint from students when working is teams is the concept of social loafing [12]. Social loafing occurs when one or more member of the team refuses to complete their fair share of the team’s work. Self and peer evaluation has been found to be the most effective method of reducing social loafing in teams. When the individual contributions made by team members can be quantified and reported, social loafing can be largely eliminated. Another method of reducing social loafing is to encourage each team member to have a unique contribution to the team. Unique contributions are easiest to encourage in multidisciplinary environments such as Capstone projects but can be more difficult in Cornerstone design projects as the students all have similar pre-existing skills.

D. Feedback and Mentorship

Compared to technical subjects, design can be much more ambiguous and subjective. Usually there can be multiple solutions to a problem, and the path taken to reach a solution can vary greatly. Coupled with the extensive amount of time required to complete one design project, students can become lost, lose motivation, or become stuck in non-productive modes of thinking. In industrial settings, projects will often follow a stage-gate process with milestones and checkpoints to ensure that projects remain on track. In a course context, student deliverables will match these milestones, and students will receive feedback in the form of marks and comments. Giving meaningful feedback can be difficult, particularly if student have difficulty articulating their thought process. Simply relying upon written feedback can lead to students continually making the same mistakes or failing to internalize corrections or suggestions. Often this is linked to “concept fixation” which is common for early designers [16].

III. Experiences and Discussion

A. Course Context

The courses described in the remainder of this paper is the second and mechanical engineering design project courses at York University's Lassonde School of Engineering. This course has been run for 3 years and has been updated each year based upon feedback and reflections from previous iterations.

At this point in their academic career, students who participated in this course had taken the prerequisite physics and math courses, as well as two first-year introduction to engineering design courses. The introduction to design courses included exposure to the design process, design-for-x, various creative thinking and innovative design heuristics. These courses also included a team-based design project; however, this project was taken only to the conceptual design phase, emphasizing needs analysis and brainstorming techniques. Additionally, students have been introduced to CAD modelling in SolidWorks™ and were given the chance to 3D print their designs. Additional relevant courses include an introduction to Machine Element Design which was run concurrently with the design project course and Mechanics of Materials.

The goal of this course is to give students an opportunity to experience the complete design process as well as promote good teamwork practices. Integrating as many of the skills and theories to which students had been introduced up to this point was one of the primary driving factors in the choice of the projects. By incorporating the various elements of the undergraduate curriculum into the project, students will be able to see practical applications of their theory as well as observe how interrelated their seemingly distinct core courses can be.

B. Past Projects

For the reasons mentioned previously, we chose to proceed with hypothetical projects for this course. We had specific goals of incorporating elements of physics, mechanics of materials, machine element design computer aided design (CAD) and rapid manufacturing. All student teams were given the same design challenge. A portion of the grade was based upon the relative performance compared to the other teams to promote friendly rivalry and ensure students move beyond a design that "just works" and optimize their design.

Each year the project changed, but some elements remained common. First, some form of energy transformation was included in all projects. Second, low strength raw materials were supplied to make the structural design non-trivial and ensure that students considered the material properties as a design variable. The variety of materials available was limited to encourage creativity in a constrained environment. Electronic components were excluded or extremely limited to place emphasis on the core mechanical principles desired, and to ensure that all students had an equal understanding of the theory.

Teams assumed the role of a design team competing for a design contract. They are given a design brief with a set of requirements and constraints, as well as the performance metrics by which they will be evaluated.

In the first iteration of the course, students were tasked with designing a scale version of a car that would store energy for locomotion in a spring. Limitations were placed upon the size of the vehicle, and the loading force; the loading force was much lower than the force required to extend the available springs. Performance was based upon vehicle weight and distance travelled on a single charge. Students applied principles of gear design, force and mechanical advantage, friction and strength of materials.

The second project had students design a small generator that would be powered by a raised weight of fixed mass. The context given was that they were designing a device that could be used as a cell phone charger, or small light source in remote communities. Students were given a small dc motor, and limited materials (high density fiberboard, metal rods, machine screws and nuts, glue). All designs had to mount to a standard fixture. Teams were evaluated on the value of the materials their design used and the length of time that they were able to sustain a 4V output from the generator. Gear train design, strength of materials and motor characteristics were some of the knowledge emphasized.

The third iteration took inspiration from a news article that showed children making a dangerous river crossing suspended on a single rope. Students were tasked with designing a small, battery powered carriage that could carry a basket with a mass across a single rope. The rope was placed at various inclines, and the performance of the designs was evaluated on the speed of crossing the rope, and the total cost of the designs.

All of these design challenges appeared, to the students, to be simple, but as they began to apply their engineering knowledge to the analysis and design process, they found that even simple challenges can be complex.

C. Team Creation and Teambuilding

A team size of 4-5 was chosen for this course as the literature highlights that larger teams can be more susceptible to social loafing, and teams smaller than 3 may not have all of the skills required to complete the task [17]. Of the three possible group formation methods (self-selected, instructor-selected or random), instructor-selected was chosen as it is generally regarded as the most effective method [17-18]. Students were required to complete a questionnaire at the beginning of the term, and students were distributed based on a number of criteria.

In the first iteration, the primary criteria by which students were assigned groups was personality based. Students completed an online Myers-Briggs personality assessment with the goal of distributing different personalities. While teams created with similar personality types tend to have better communication and reduced conflicts, teams with diverse personalities can have enhanced problem-solving skills as the weaknesses of one member can be complemented by the strengths of others [19]. In subsequent iterations, personality or creativity style profiles were used more as a teambuilding exercise than the primary grouping criteria.

Other criteria which were taken into consideration at a lower weighting during team formation were overall GPA, available free time, and previous skills. Subsequent iterations focused on distributing students primarily upon GPA and students comfort with hands-on activities as those were found to be better indicators of successful students.

The first two weeks of tutorials were dedicated to encouraging teams to work together effectively. During the first tutorial, a roundtable discussion of effective teamwork skills was conducted. This was aimed at address some of the common issues with teamwork, and highlighting techniques to overcome them. Students were then introduced to their teams, and asked to choose a team name. Students were asked to complete a team policies and expectations contract (modified from [17]). This contract outlined what was expected of each student when working in a team, such as communicating promptly and completing assigned work on time. The contract also contained a policy for dealing with social loafing or uncooperative members within teams. Students were encouraged to modify or add policies at their own discretion. The contract ensured that all students understood the policies set out by the course, and gave them a sense of ownership over the performance of their team. During the second tutorial, a teambuilding exercise was conducted using the LEGO Serious Play™ Platform. Students used a guided LEGOTM building experience to share previous team experiences, with a goal of helping to build trust between members of the group.

D. Peer-Evaluation

Peer- and self-evaluation was included as the major tool in reducing social loafing, monitoring conflicts within teams and promoting collaborative learning. Two online peer evaluation tools, CATME and TEAMMATES were used in various iterations of the course. Students preferred to use TEAMMATES as it was significantly less time required to complete an evaluation at the cost of accuracy and repeatability. The peer evaluation instrument was used to rate the performance of each team member in terms of contributing to the team, interaction with the team, keeping on track, quality of work, and more. Peer- and self-evaluation surveys were conducted after the submission of a major deliverable. Students were given participation marks for taking part in the surveys and based upon the results of the final peer evaluation survey, a modifier was applied to their final report mark. The results of each of the peer evaluations was released to the students anonymously so that students could receive feedback regarding how the rest of the team perceived their contributions and communication. The peer evaluation tools allowed students to confidentially communicate feedback to each other, and course directors. Intervention into poorly performing teams was done based upon these peer evaluations.

Despite the work on developing strong teams, and the rigorous peer evaluations, one of the major complaints with the course has been team dysfunction. Primarily it is related to social-loafing, real or perceived. Often, some students become very engrossed in the project, leading them to spend significantly more time on the project than other members of their group. While the other team members contributed in the form of ideas and workload at a level that, in another group, would be considered equal, their perceived contribution in that group is lower. Identifying these groups and working with them to normalize expectations or identify new ways of collaborating can help to prevent conflicts.

Another common complaint from students is that they feel their ideas and opinions are not respected by their team mates. This can lead to students taking a passive role in their teams, and eventually lower levels of perceived participation. Despite updated training on how to promote contribution from everyone, the issue still arose. These groups require early intervention and continual monitoring to prevent issues.

E. Design Process and Deliverables

The structure of the deliverables was set up to follow the engineering design process. The design process highlighted for this course was the popular VDI 2221, Systematic Approach to the Design of Technical Systems and Products [20].

Design fixation has led to students skipping major steps in the design process, or beginning with a final design in mind, and working backwards in the design process to tailor preliminary design steps to meet their desired design. This led to many students' designs failing to solve the desired problem, not meeting constraints, or arriving at a poorly optimized solution. To emphasize the importance of sequentially following the design process, reports corresponding to VDI 2221 design process "results" were collected at predetermined intervals during the term.

Following the submission and marking of each report, they were returned, and course instructors met with each team to discuss their reports, and any errors. Students were given time to reflect, ask questions, and make improvements to their ideas so that they could be used in subsequent design steps. These review sessions were essential in ensuring that students understood the subject matter and constantly worked to improve their designs. Frequent and face-to-face feedback and discussion was found to be by far the most important part in ensuring that students remained on track and internalized feedback from their deliverables.

Following the completion of the students' Definitive Layout, and 2 weeks before the final competition, students were required to build and test a prototype. The prototype was crucial in ensuring that students identified unforeseen errors in their design, limitations of the materials and/or manufacturing methods.

The final design report contained descriptions of the final design, CAD models, and testing results. It was also used as a final reflection on the overall design process. Students were asked to use the knowledge and experience that they had gained over the design process and reflect on how they would have approached each of the design phases differently.

IV. CONCLUSIONS

Developing a design project course for first and second year students can be difficult, but the tools available to course developers can help create a successful program. By understanding the skills and knowledge that the students have developed, a project can be tailored to be challenging, yet attainable. 3D printing and other rapid prototyping tools can allow projects to be designed, built and tested, all during a single term. By leveraging freely available online tools, we were able to implement the major components of PBL and CL.

For most students, this is their first opportunity to fully design, analyze, build and test a design. Whether or not students are able to create a high performing design, they learn valuable lessons in design and manufacturing, as well as practical applications of the theory presented in their engineering courses. Most difficulties in running this course are due to teamwork problems. Special consideration for teamwork training, monitoring and interventions must be made to ensure students have a successful project.

Including design activities, particularly team-based design projects, during the early years of engineering curriculum can help to develop this skill and practices that industry demands.

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