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Engineering Design EDUCATION: When, What, And HOW

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ABSTRACT

This paper presents an innovative, interdisciplinary, design-and-build course created to improve placement, content, and pedagogy for introductory engineering design education. Infused at the freshman level, the course aims to promote expert design thinking by using problem-based learning (PBL) as the mode of delivery. The course is structured to actively engage the students in the various phases of a prescriptive design-and-build cycle using ill-structured, open-ended problems inspired from industry, and is supported by technological tools such as robotics kits and rapid prototyping machines. One of the main contributions is the integration of the prescriptive design cycle with PBL to promote effective inquiry and the systematic, iterative interplay between divergent and convergent questioning in the engineering design process. The inherent alignment of PBL pedagogy and the prescriptive design cycle enhances students' ability to tackle complex challenging problems and reach optimal solutions by following an iterative loop of divergent-convergent processing and decision making. In the post-analysis, the course has two significant positive impacts on students: 1) as measured by a newly developed design attitudes survey, course graduates are 20 ± 5% more likely than other engineering students to express attitudes consistent with professional engineers regarding problem-solving practices in the engineering design process, and 2) a measure of teams' adherence to the course's prescribed design cycle are moderate-to-strongly correlated ($\rho \sim 0.66$, > 90% confidence) with the quality of the finished design, as measured by live, in-class demonstrations.

Keywords: Freshman Design, Design Thinking, Design Cycle

INTRODUCTION

Although the role of design, an interdisciplinary central activity in engineering education, has progressively evolved over the years, many educators agree that further critical improvements are warranted on three different levels: placement in engineering curricula (*When*), content (*What*), and instructional pedagogy (*How*) (Evans *et al.*, 1990, Beaudorn *et al*, 1995), Froyd and Ohland, 2005, Dym, 2004, Dym *et al.*, 2003, 2007, Dutson *et al.*, 2007, Sheppard *et al.*, 2009, Litzinger *et al.*, 2011, Cheville and Bunting 2011, King, 2012).

Placement

The recent infusion of cornerstone engineering design courses at the freshman level was mainly motivated by the curricular disconnect in the traditional science model of engineering education, in which the first two years are typically devoted to basic sciences and mathematics, with minimal exposure to "real-world" engineering problems (Froyd and Ohland, 2005, Dym *et al.*, 2003, 2007, Sheppard *et al.*, 2009). This model poses several potential problems as summarized by Froyd and Ohland (2005), including low student retention due to the delay of explicit connections to engineering; academic challenges perceived by students due to the curricular detachment between their mathematics and science courses and their applied engineering courses; and suboptimal performance of students perceived by faculty as a result of this time lag (Froyd and Ohland, 2005). The long-term impact of this curricular disconnect, which clearly delays student exposure to engineering integrative thinking and experience, potentially extends to professional practice. Many educators agree that students adhering to this model may face challenges in meeting industry's need for engineers who are not only technically proficient in their respective domains, but who also have good non-routine problem-solving and critical thinking skills, teamwork and communication skills, as well as skills for knowledge acquisition, systematic inquiry and continued learning (Marra *et al.*, 2000, Dutson *et al.*, 2007, Dym *et al.*, 2007, Sheppard *et al.*, 2009).

During the last decade, the Accreditation Board for Engineering and Technology (ABET) has also revised its accreditation process towards bridging the gap between academia and industry, prompting significant changes in the traditional engineering education model (ABET report, 2000). For example, ABET 2000 standards recommend the introduction of design courses at the freshman level, as well as the integration of design courses throughout engineering curricula (ABET report, 2000). In order to meet ABET's learning outcomes-oriented assessment and criteria, engineering programs now must demonstrate that their students have an ability to "design a system, design and conduct experiments, function on multidisciplinary teams, and to identify, formulate, and solve engineering problems". Programs that mainly rely on the senior level or capstone design courses to develop these fundamental skills are disadvantaging their students by delaying their engagement in solving real world problems and hence meeting the complex challenges of today's engineering practice (Marra *et al.*, 2000, Dym *et al.*, 2003).

Content

The second level of crucial improvement to the current practices in engineering design education is content (Evans *et al.*, 1990, Dym *et al.*, 2003, Dym *et al.*, 2007, Dym and Little, 2009, Sheppard *et al.*, 2009). Despite the notable progress in recent years, design courses taught in diverse engineering programs continue to suffer from a clear disconnect with the system design thinking and process required to meet the continuous metamorphosis of modern engineering practice (Creed *et al.*, 2002, Dym *et al.*, 2007). Design thinking according to Brown is the methodology that spans the full spectrum of innovation activities with human-centred design culture, typically integrating three principal phases of inspiration, ideation, and implementation (Brown, 2008). Successful designers of the 21st century require a new set of skills, above and beyond their technical training in order to match clients' needs with what is technologically feasible, within a viable business model and implementable strategy. Unfortunately, research shows that today's average engineering student may graduate without acquiring the necessary skills or the sufficient practice in proper design thinking methodology (Creed *et al.*, 2011, Dym *et al.*, 2009). He or she may also lack the training for the iterative, systematic process of inquiry and knowledge acquisition, potentially reducing their capacity for innovation, productivity, and business competitiveness.

In their article on engineering design thinking, teaching and learning, Dym *et al.* discuss design thinking as an intelligent complex process of systematic inquiry and learning (2005). They argue that while in recent years the presence, role, and perception of engineering design have improved, further improvements are necessary. For example, while current engineering design curricula successfully promote systematic questioning or convergent thinking in capstone design courses, there is a lack of clarity and consequently little initiative in teaching divergent inquiry in a design context (Dym *et al.*, 2005). As defined by these authors, the key distinction between the two classes of inquiry is that convergent questions operate in the knowledge domain (questioner attempts to converge on facts), whereas divergent questions span the concept domain (questioner attempts to diverge from facts to possibilities). Effective inquiry in design thinking, according to the review article, should be an iterative, divergent-convergent process spanning both the concept and knowledge domains in order to tackle the complexity and sophistication inherent to the 21st century grand challenges for engineering.

Dym *et al.* (2005) also explore the various dimensions of design thinking and design thinking skills. They also discuss in detail the characterization of design thinking and the required skills for the complex cognitive design process. These skills include the ability to:

1. View design as an iterative loop of divergent-convergent thinking;
2. see the big picture or systems thinking and design;
3. reason about and address uncertainty;
4. make decisions;
5. function effectively as part of a design team; and
6. develop fluency in the several languages of engineering design, including verbal, graphical, and number representations.

The article also stresses the importance of "system design" and "system thinking" skills as necessary means for addressing the complexity of modern world design. These skills include design thinking in a system's context, reasoning skills about system design uncertainty, skills for approximation and making estimates, and experimental design skills (Dym *et al.*, 2005).

Brown (2008) describes the design process as a system of "spaces" rather than a predefined series of orderly steps, where typically design projects pass through three spaces of inspiration, ideation, and implementation. These spaces integrate all the related activities forming a continuum of innovation. He also proposes recommendations for making design thinking an integral part of the innovation process. These include early introduction of design thinking in the innovation process, human-centered design approach, early and frequent experimentation, seeking expert help, blending big and small projects, not constraining design thinking and innovation with existing budgets, recruiting interdisciplinary talents, and implementing the full design cycle.

MIT's new model of engineering education is another example that accentuates engineering fundamentals within the context of the actual engineering process; namely, conceiving, designing, implementing, and operating. The so-called Conceive-Design-Implement-Operate (CDIO) MIT initiative focuses on the various dimensions of engineering design and the value of systematic questioning in a design context. The main motivation behind the initiative was the widening gap between engineering education and real-world demands. Curricula at MIT were modified to include team-based, design-and-build projects which progress in complexity toward an elective capstone design course that requires students to integrate and apply their cumulative knowledge to a comprehensive, industrially-inspired project (http://web.mit.edu/edtech).

Pedagogy

Research shows that although the delivery of design courses has improved in recent years, few engineering schools/educators take advantage of the wide spectrum of available pedagogical models in engineering education, particularly in design education (Marra *et al.*, 2008, Litzinger *et al.*, 2011, Prince, 2004, Prince and Felder, 2006, 2007). Prince and Felder (2006) investigated the effectiveness and implementation of various inductive teaching methods as compared to traditional deductive teaching. Inductive teaching methods are methods of course delivery in which instructors begin by presenting students with a specific challenge, or a complex real-world problem. The students are consequently "coached" to self-learn upon recognizing the need for theories, facts, skills and concepts. Examples of inductive methods include discovery learning, inquiry-based learning, problem-based learning, project-based learning, case-based learning, just-in-time-teaching, and active and cooperative learning (Prince and Felder, 2006). These innovative learning styles are quite different from the traditional deductive technique in which instructors start with theories and mathematical models, and then move to textbook examples, which may or may not ultimately extend to real world applications (Prince and Felder, 2006). The main shortcomings with deductive teaching lie in the low effectiveness of didactic lecture instruction to passive audiences for producing conceptual change, potentially resulting in low retention rate of engineering and science students, in addition to the curricular disconnect between theory and practice (Prince, 2004, Prince and Felder, 2007, Litzinger *et al.*, 2011, Kardash and Wallace, 2001).

In their recent article on engineering education and development of expertise, Litzinger *et al.* (2011) define effective learning practices as those that support the development of expert professional practice. They explore and recommend a list of affective, meta-cognitive, and cognitive instructional practices that create effective learning experiences. Problem-based learning (PBL) is recommended as a learning pedagogy towards developing the necessary analytical and complex problem solving skills needed to tackle multifaceted challenging engineering problems.

H.S. Barrows, one of the pioneers who three decades ago developed and implemented problem-based learning in medical education at McMaster University, defines PBL as "a learning method based on the principle of using problems as a starting point for the acquisition and integration of new knowledge" (Barrows, 1985). As a form of cognitive apprenticeship, the traditional teacher and student roles change in PBL. The students or "apprentices" are empowered to assume increasing responsibility for their learning. The teacher, on the other hand, assumes the role of a facilitator or "master tradesman" coaching and scaffolding expert problem-solving strategies (Newstetter, 2006). The progression of a PBL cycle is typically as follows: (1) student teams are presented with a complex, ill-structured problem. (2) Students define the problem and identify the skills needed to solve it. (3) Students engage in learning first independently and then cooperatively to build their knowledge base. (4) the cycle is repeated until the students arrive at an acceptable solution (Litzinger *et al.*, 2011).

Numerous researchers have shown that PBL is an effective pedagogy in medical education which encourages students to be active participants in shaping their learning, increases their retention of knowledge over a long period, and enhances the transfer of concepts into clinical situations (Kou and Mehta, 2005). Other advantages of PBL as detailed by Barrows (1998) include increased self-direction, higher comprehension and better skill development, interpersonal skills and teamwork, and self-motivated attitude. Barrows also points out certain challenges in PBL administration including quality control, faculty training, heavy resources, and difficulty of assessment.

The adoption of PBL as a learning pedagogy in engineering education was mainly motivated by the 1997 National Science Foundation (NSF) report *(Systemic Engineering Education Reform: An Action Agenda)*. The report recommended reform in engineering education particularly stressing teamwork, better industrial links, and the interjection of problem/project based learning (NSF, 1997). In the last decade, various engineering educators reported on the implementation of PBL as a pedagogical model. Huang *et al.* (2006) compared traditional pedagogies, such as subject-based learning, cookbook laboratories, and group work, with non-traditional, active engagement pedagogies, such as problem-based learning, project-based learning, cooperative and collaborative learning. They also considered mixed learning methods including subject + project assisted and subject + cooperative learning models. Four main factors were used to evaluate the risks and benefits of a particular learning pedagogy, namely, student factors, instructor factors, course factors, and institution factors. Their results showed that while non-traditional pedagogies have advantages and disadvantages, it is quite beneficial to incorporate active learning components in engineering education. Kou and Mehta (2005) used PBL in conjunction with the Lego RCX System in an Engineering Measurements course as part of the Mechanical Engineering curriculum at North Dakota State University. Their two year consecutive study used three different teaching methods: (1) traditional; (2) PBL; and (3) combined. Their results showed that the PBL method (used partially or fully) significantly improved analytical and open-ended problem solving skills, cooperative team work skills, as well as written and communication skills. The effects of a team-based PBL freshman design course at Pennsylvania State University on student intellectual development were quantitatively measured by Marra *et al.* (2009) using the Perry scheme. The Perry model mainly suggests that the students' cognitive processes develop gradually over time and could be quantified using 9 levels of increasing complexity and maturity of intellectual development. The design experience correlated positively with enhanced student intellectual development. The authors recommended a longitudinal study to shed more light on the quantification of the curricular reform efforts. In their paper, Brodeur *et al.* (2002) described several problem-based learning experiences in undergraduate aerospace engineering at the Massachusetts Institute of Technology (MIT). They recommended the integration of PBL across all four years to provide a natural progression from structured problems, which require high levels of faculty direction and support, to unconstrained and more complex problems that resemble real life situations. Their results reflected that students at MIT who underwent the PBL learning model reported a greater understanding of core science and engineering courses, found learning more interesting and engaging, and established better connections between their education and real-world applications. Dym and Little (2005) also advocated the use of PBL, labeling it as the currently "most-favored" pedagogical model for teaching engineering design. Based on their literature review, they established that PBL courses (freshman and otherwise) improve retention rates, student satisfaction, diversity, and learning provided they are designed and administered properly. Their article explored a basic framework for ensuring quality control and enhancement in adopting PBL in engineering design education.

It is noteworthy to point here that in addition to its well-established value as an effective pedagogy in various education models, the use of PBL is particularly advantageous in engineering design education due its inherent alignment with the design thinking and process. For example, a review of the design cycle and the PBL cycle reveals that both cycles usually start with ill-structured, open-ended, complex problems and follow an iterative loop of divergent-convergent processing and decision making to reach an optimal solution. In both cycles, it is imperative to have effective team and communication skills, "big picture" or system vision, systematic questioning, and decision-making abilities including addressing estimates and uncertainties.

This work presents an innovative, interdisciplinary, cornerstone engineering design-and-build course that addresses improvement in engineering design education at three different levels of placement, content, and pedagogy. The course, which is infused at the freshman level, is intended to promote systematic design thinking and culture using a PBL, inductive problem-based learning method of delivery. It is structured to actively engage the students in the various phases of the prescriptive design cycle (problem formulation, conceptual design, preliminary and detailed design, rapid prototyping, interface and control programming, and design communication) using ill-structured, open-ended problems inspired from industry. Towards this goal, three modules are integrated: a LEGO Mindstorms robotics kit, a C++ interface, and a 3-D printer as tools to be used during the prescriptive design process. Specially designed rubrics (see Khalaf *et al.* 2010) are used to assess and quantify the skills essential to design thinking: systematic inquiry silks, knowledge acquisition skills, problem solving skills and team dynamics skills. This paper describes the course structure, management and challenges, as well as ongoing work towards devising effective methods of assessment.

COURSE OVERVIEW

This section describes the course structure, course management and student performance assessment as aligned with the course objectives.

Course Structure

The new freshman engineering design-and-build course promotes systematic design thinking and process using an inductive pedagogy, PBL, as the mode of delivery, in conjunction with technological tools such as robotics kits, a rapid prototyping machine, and C++ interface. Towards this goal, several interdisciplinary, industrially inspired, open-ended problems/projects are introduced to student teams (3-4 students/team). During the first class, each team is provided with a "tool kit" (Mindstorms LEGO kit) to be used as a platform for various parts. It should be emphasized that the LEGO kit is merely used to help populate a stock room, in contrast to courses that use the kit contents exclusively and/or to solve closed-ended problems. In addition, the students have full access to a state-of-the-art rapid prototyping 3-D printer for any needed custom-made parts, and are encouraged to use any "out of the box" parts and sensors as appropriate. Final designs are typically a hybrid mix of parts from LEGO kits, custom parts made using the 3D printer, as well as other components from the lab's stock room. Various other tools are introduced into the course depending on the problem at hand, such as Parrot AR drone and Working Model.

The course is structured to actively engage the student teams in the various stages of the prescriptive design cycle with particular focus on system design thinking characteristics and skills (see section 1.2, Content). The teams iteratively proceed from problem formulation, to conceptual design, to preliminary and detailed design, and finally to design communication. The authors based this structure on the five stage prescriptive model of the design process by Dym *et al.* (2003) with some modifications to meet the course objectives (stages 3 and 4 (preliminary/detailed design) are merged into one since the students at this level do not have enough theoretical background to optimize a design (i.e. produce a "detailed" design), and design prototyping/building is added to the process in order to give the students a flavor of real-life product design and development). The students are given three real-life, open-ended, ill-structured design problems per semester. The problems progress in complexity towards the final one, which requires the students to integrate the entire prescriptive design cycle and demonstrate understanding of formal design thinking process, strategies, as well as effective use of tools, such as objective trees, pair-wise comparison charts, functionality analysis, and morphological charts. The process can be summarized as follows:

Stage I: Problem Definition/framing: student teams are given a "real world" engineering problem using a client statement as a start for the communication. The statement is typically designed to be ill-posed and open-ended in nature with real constraints in order to narrow down the options and converge to a solution in a timely fashion. The students are then encouraged to use formal design methods in defining and framing/revising the problem, as used by experts/engineers, such as pruned lists of objectives, objective trees, pair-wise comparison charts, use-value analysis, etc.

The expected outcome of this stage of the cycle is a well-defined problem statement with clear objectives and metrics, and clearly identified design constraints, in alignment and consultation with the client (instructors).

Stage II. Conceptual Design: An iterative, divergent-convergent approach (Dym *et al.* 2005) is adopted during this stage. Student teams are coached to engage in the various activities involved in the conceptual design process. The process begins with brainstorming, where the students are introduced to and encouraged to use various generative design questioning tools such as the 6-3-5 and the C-sketch techniques, as described by Dym and Little (2003). One of the added values of these techniques is the ability to promote and monitor positive team interaction and group dynamics. The next step in the conceptual design process involves identifying the functions that the design must perform and formulating the design requirements. Formal means such as function-means trees and morphological charts are used to establish the functions and their specs, as well as the means for performing these functions.

The students are encouraged to follow an iterative divergent-convergent process to think out of the box and divergently consider the various design alternatives. They are then coached to systematically refine the design space, keeping in mind the client needs and constraints and the project's viability based on limited proof-of-principle modeling and tinkering. Design alternatives are generated at this stage, quantified with appropriate metrics, and converged towards a final design. The expected outcome of stage II of the cycle is the convergence of each student team on a final design optimally selected based on decision selection matrices from the design space.

Stage III: Preliminary and Detailed Design and Build: based on the conceptual design selection, the student teams model and build the selected design prototype using available tools such as parts, motors, and sensors from their toolkit (Lego Mindstorms), Pro Engineer solid modeling software, as well as, any extra purchased and/or custom-made parts that they prototype as needed using the 3-D printer. They also use NXT++ (the software library integrated with the Lego Mindstorms) and C++ sequential command line programming in order to interface with and control their designs.

Teams go through iterative loops of evaluating/questioning their design before prototyping their solutions. They are coached to use the holistic system-level approach in design assessment and evaluation, and are encouraged to continuously and systematically question their choices. Instructors at this stage act as coaches to help the students in their assessment and inquiry sessions. Microsoft Project is used as a tool in creating and defining timelines and Gantt charts. A leader of a group is expected to manage and follow up on the members' tasks and assignments. The outcome of this stage is a finalized system design, which is tested and evaluated.

Stage IV: Design Communication: throughout the course, student teams use the Course Management System Moodle for group discussions. In these discussions they brainstorm, exchange ideas, post meeting minutes, as well as, CAD drawings and hand sketches as related to their designs. Upon project completion, each team is required to submit a written report that includes all the design details, drawings, figures and tables, and the C++ computer code developed. In addition, each team has to do an oral demonstration/presentation to peers and instructors. During the demonstration, the instructors arbitrarily question each team member to insure individual accountability. Certain projects include a competition among teams in which a winning team is chosen based on peer evaluations. The final project is presented via a formal Power Point presentation, which must include participation from all team members. Each team also generates a final poster reflecting the entire design cycle and fully describing the design process.

Problem Selection: An Example Case Study

The design problems selected for the course are of multidisciplinary nature spanning various engineering disciplines such as mechanical engineering, biomedical engineering, aerospace engineering, and civil engineering. Each problem is given for a period that may vary from 1 week to 5 weeks based on the level of complexity. A special lab/studio is set for the course (details outlined in section 2.2).

Case Study: Design of a Deployable Cantilever Beam

Client Problem Statement*: A deployable beam, cantilevered to a provided wall is needed to carry loads up to 250g at the tip. The tip deflection from horizontal plane should not exceed 32mm at any load case. The cantilever beam must be initially packed within a volume of max 15cm x 15cm x 20cm, then deployed to a length of at least 50cm, measured from the wall (see Figure 1a and 1b). The deployment phase must be carried out by a mechanism within the volume (i.e., no external forces by humans). Control system of deployment (such as the NXT brick for on/off etc.) can be outside the volume (Figure 1b).*

Deliverables:

For this problem the students were asked for the following deliverables

- *Report including the brainstorming exercise, objective tree, function mean tree, morphological chart, decision selection matrix, as well as any other brainstorming and decision-making exercises.*
- *Drawings of all alternative designs using CAD drawings, hand sketches and any other means.*
- *Code used in C++ that deploys the system including the closed-loop control system for the tip deflection.*

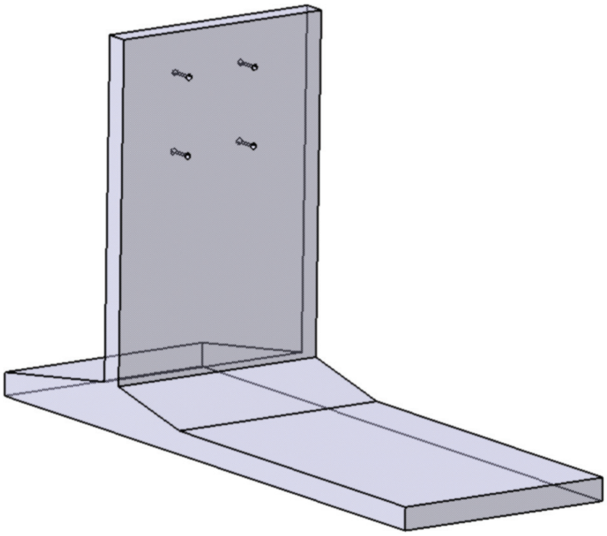

Figure 1a. Provided Wall, With Four Holes For Attachment.

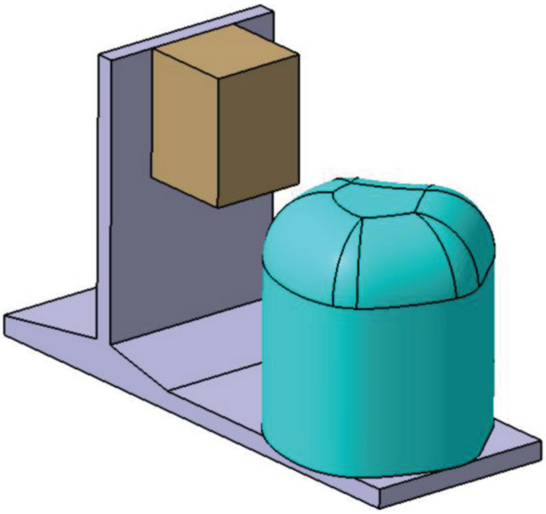

Figure 1b. Packed Beam System (Brown) And Sensing/Control Unit (Turquoise)

- *Drawings of any custom-made parts to be prototyped using the 3-D printer in integration with parts from the Lego kit.*

The following section introduces a sample solution of one of the teams to the above problem.

Revised Problem Statement

"The client is asking us to design a deployable cantilever beam. This beam should be packed in a box that has 15 cm x 15 cm x 20 cm dimensions. The beam has to be mounted in the wall by four bolts with equal distances between them that are 10 cm. The beam should have a minimum length if 500 mm when it is un-packed from the box. It has to withstand a 250 grams load as maximum. The load should be stable while being on the beam and it should not slide or fall off the beam. If the maximum deflection of the tip of the beam exceeded 32 mm the beam should adjust its situation automatically and alter this deflection. At least two functional parts (not dead loads) have to be designed using PRO/E and printed using the 3D printer. The period of time in which the design should be ready is 4 weeks starting from 12th of Oct., 2011 until 16th of Nov., 2011. Good results should be obtained from testing more than once."

The revised problem statement of this team (Team 1) reflects a clear grasp of design thinking and process, as well as proper use of the formal tools and methods for the iterative design process. Team 1 has successfully clarified the client's initial statement and translated it into meaningful objectives and constraints using tools such as an objective trees and pair-wise comparison charts. The objective tree (a hierarchical list of the client's objectives and goals (Figure 2) lists the design's primary objectives and sub-objectives based on the client's statement. The team continued to frame the problem using a pairwise comparison chart (a chart used for rank ordering and identifying the relative value of the client's objectives) (Table 1)

Table 1 shows the pair wise comparisons used to identify the most important goals from the objective tree in Figure 2. It is clear from the tables that according to this comparison the most important goal for the beam was not to exceed the allowed tip deflection. This goal was clearly identified in

Objective	Safe	Accurate	Within Size Limit	Smart	Stable	Tolerates weight	Does not deflect	Total
Safe	XXX	0	1	1	0	0	0	2
Accurate	1	XXX	0	1	0	0	0	2
Within Size Limit	0	1	XXX	1	0	0	0	2
Smart	0	0	0	XXX	1	0	0	1
Stable	1	1	1	0	XXX	0	0	3
Tolerates Weight	1	1	1	1	1	XXX	0	5
Does not deflect	1	1	1	1	1	1	XXX	6

Table 1: Team 1 Pair-Wise Comparison For The Deployable Cantilever Beam Project.

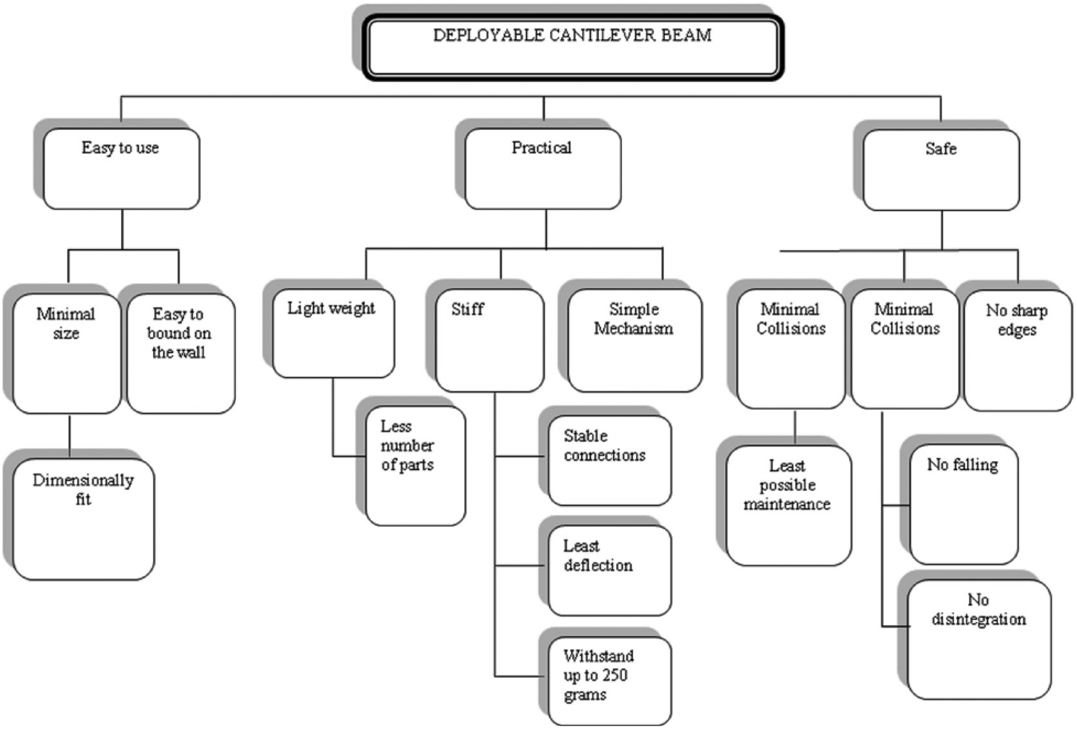

Figure 2. Team 1 Objective Tree For The Deployable Cantilever Beam Project.

the revised problem statement. The weight and stability were also part of the revised statement. This shows that the students did follow the procedure to reach the revised statement.

Once the client's problem statement was revised or framed, Team 1 moved to the second phase of the prescriptive design cycle: conceptual design. This phase entailed a systematic iterative interplay between divergent and convergent questioning to generate design alternatives and then refine them towards choosing a final design. Team 1 established the design functions based on the revised client's statement; specified function specs and alternative means for achieving those functions; generated design alternatives presented in Figure 3. The team established appropriate metrics that were used to measure whether the design objectives were achieved. These metrics were introduced and evaluated in Table 2.

Table 2 shows how the team converged to the final design by scoring based on both constraints and objectives. Looking at these numbers it noticed that the scoring was highly favorable of the bridge design option. This design scored the highest and it was adopted as the conceptual design for this group. Figure 4 shows examples of the some of the other Teams solutions as well as some of the parts they designed to achieve the tasks required. It is noticed that other teams who went

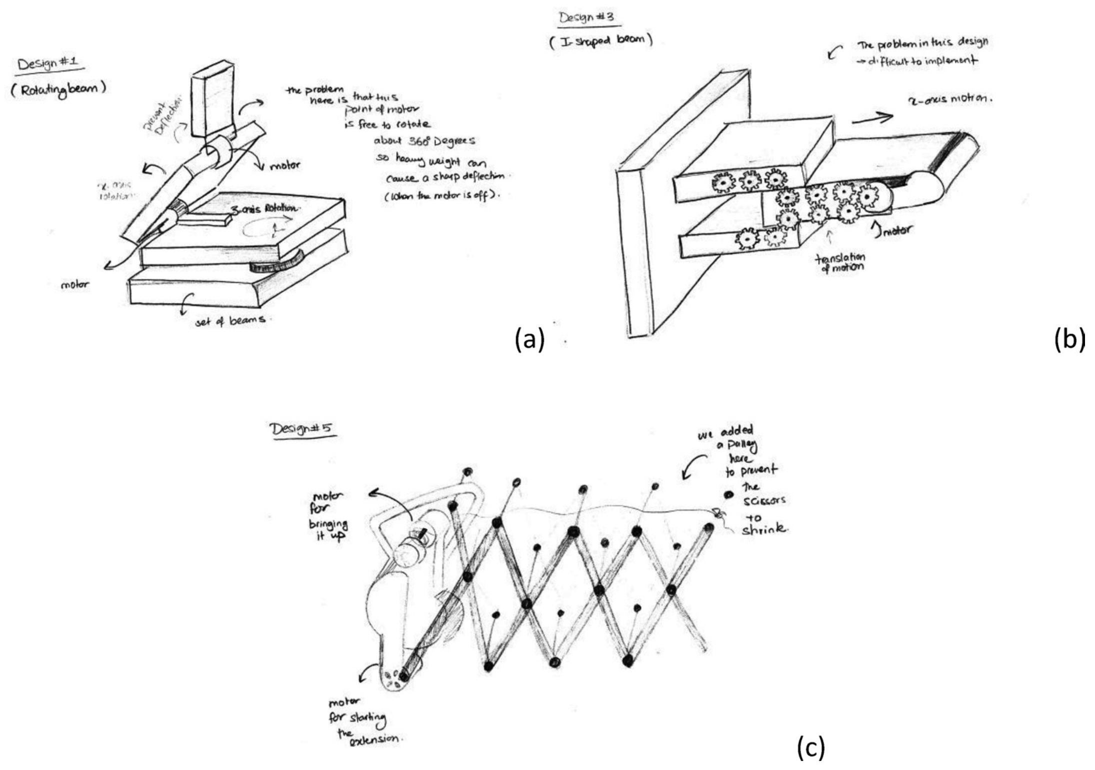

Figure 3. Alternative Designs For Deployable Cantilever Beam Project.

through the same process of design converged to other solutions; some of which were similar to Team 1 alternatives.

Course Management

The main components taken into consideration when managing the engineering design course are team formation, student performance and accountability assessment, instructor supervision, and equipment and assets as shown in Figure 5.

Team members are selected by the instructors for all projects except for the final one, where the students are asked to form their own teams. The size of each team is 3-4 members and in all cases does not exceed 4 members. The instructors select the teams balancing gender, ethnicity and academic level as recommended in problem-based collaborative learning (Newstetter, 2006). From instructors' perspective, it is challenging to select students solely based on GPA. For example, team dynamics may be different based on their analytical abilities vs. their experience in hands-on projects. So the teams were selected based on a combination of the GPA, team dynamics and instructors previous observations of team members' performance. The authors plan to look further

Design Constraints	**Zigzag Design**	**Wood Slider Design**	**Open up Bridge Design**
The size should fit the box (15 × 15 × 20)	Yes	Yes	Yes
It should be simple	No	Yes	Yes
Design should be 50 cm in length	Yes	Yes	Yes
Design should be stiff to resist deflection	No	Yes	Yes
Design should be safe with no sharp edges	Yes	Yes	Yes
Design must oppose maximum moment.	No	Yes	Yes
Design Objectives	**Score**	**Score**	**Score**
Stability	40	80	90
safety	100	100	100
Length	100	100	100
Simplicity	50	85	75
Manufacturability	60	40	80
Tolerates *Weight*	50	80	80
TOTAL	**400**	**485**	**525**

Table 2: Decision Selection Matrix For Comparison Between The Alternative Designs, Objectives And Constraints For The Deployable Cantilever Beam Project.

into the issue of team formation. Most of the time, the formation is based on internal discussions between instructors reflecting team dynamics in previous courses and projects. The first project is usually assigned a lower grade weight compared with the following projects.

Student grades are based on three types of performance assessment: self assessment, peer assessment, and instructor assessment. In self assessment, the students mark themselves and their other group members in terms of % contribution to the group effort. Peer assessment involves the students evaluating other team designs in terms of functionality and creativity on a Likert-scale. Students are also asked to challenge other teams' designs, who in turn are asked to defend their designs. The results of the self and peer evaluations are partly taken into consideration when instructors evaluate team projects. Instructors also follow up on the Moodle discussions when the team is not in the lab. Based on the contributions and the involvement in the team discussions, the highly motivated team members and contributors are rewarded.

A special lab/studio is set for the course. The layout of the lab is presented in Figure 6. The lab is equipped with hand tools, hardware (LEGO kits and 3-D printer), and PC's for the controlling and interfacing with the LEGO kit sensors. Each student group has a storage space for their LEGO kits and designs. The PC's are also equipped with Pro-Engineer solid modeling software.

The two main pieces of hardware used in the laboratory are the LEGO Mindstorms kits and a 3-D printer, both of which add value in delivering hands-on project experience. Access to the lab equipment

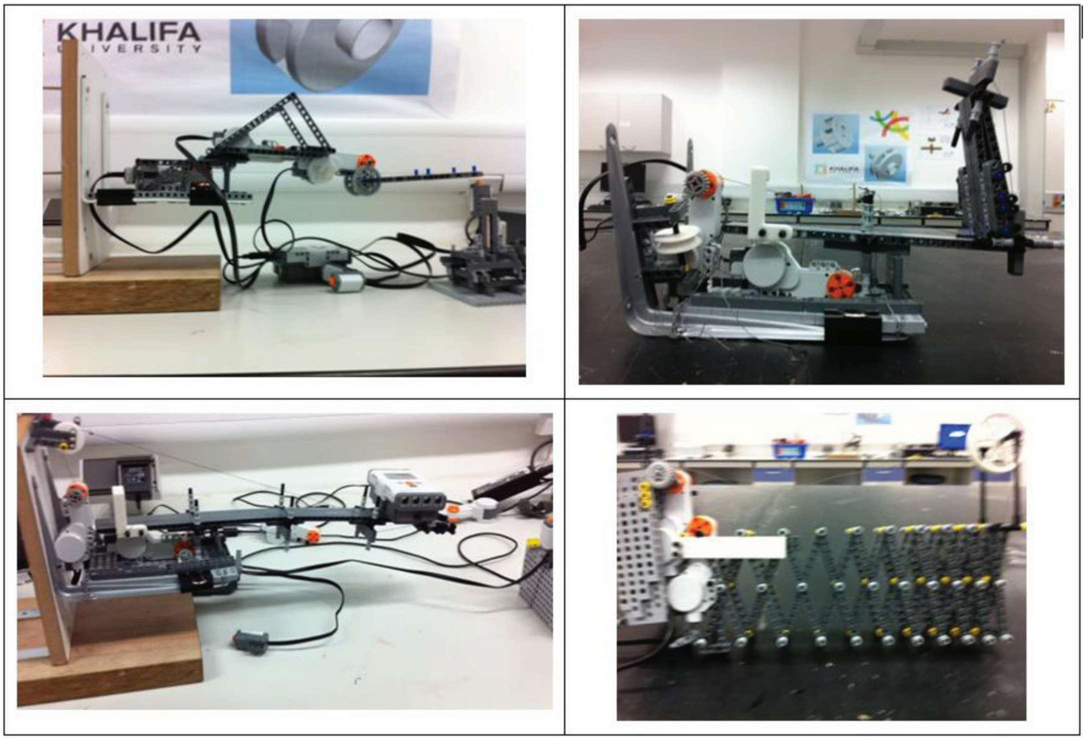

Figure 4. Student Solutions For The Deployable Cantilever Beam Project.

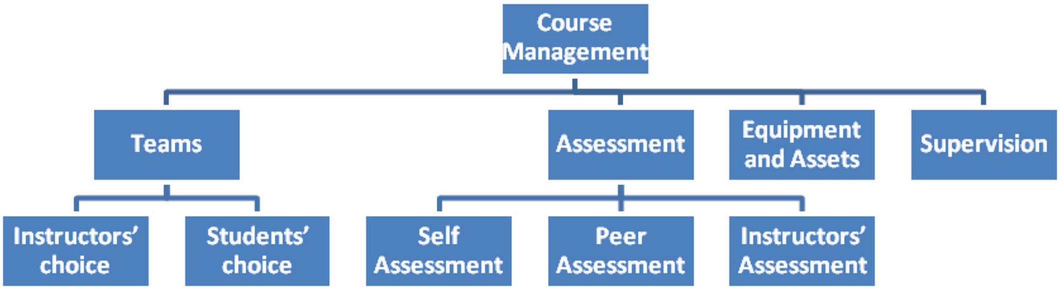

Figure 5. Course Management Tree.

is not restricted to class or lab times. Students have the opportunity to continue their work at their convenience. A lab log is kept to keep track of the time spent in the lab. Each team is assigned a LEGO kit which they sign for and label at the beginning of the course. The students are fully in charge of all their tools and kits and have to do a full inventory at the end of the course. This enhances their self-direction, sense of ownership, well as engagement in the learning process. Before prototyping

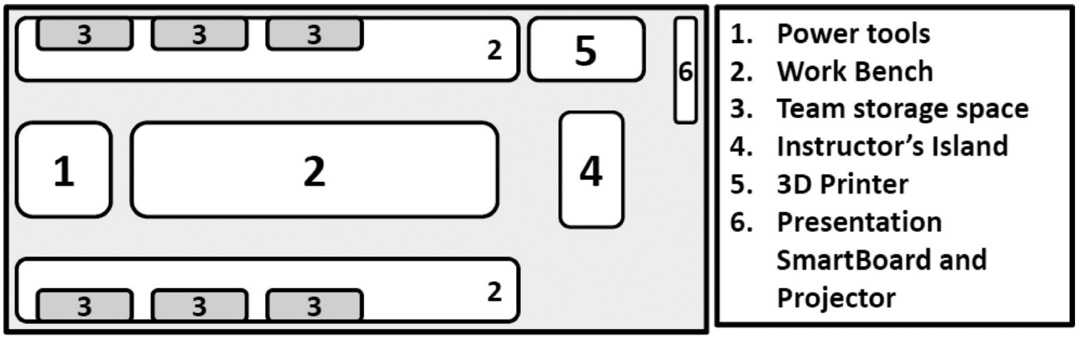

Figure 6. Schematic Diagram For Course Lab Layout.

(3-D printing), students are required to get approval of the instructor to ensure that they have systematically undergone the necessary design iterations prior to prototyping.

A team of instructors facilitate and supervise the course (two professors and one lab instructor from three different engineering disciplines). All problems/projects are solved *a priori* to anticipate any potential problems. The instructors' main role is as facilitators who monitor teams' progress and provide them with the necessary feedback, scaffolding expert problem solving strategies as needed. This is done to verify that all the members understand and participate in the various design stages of each project (individual accountability) and to ensure that the teams are able to deliver the project's requirements (team accountability). Discussions are triggered mainly through questions posed by instructors in a Socratic style, guiding the team thinking and analytical process towards achieving the target, while allowing them to self-direct and mange. The instructors also motivate the students to be fully engaged by planning peer evaluated demos, competitive events and challenges.

COURSE IMPACT ON STUDENT ATTITUDES

A major learning outcome of the freshman engineering design course is improved student design thinking and problem-solving attitudes in a team context, so that "soft" skills, such as teamwork and communication ability, are developed in parallel. Assessing this outcome is complicated by the fact that students take the course prior to most of their university-level math and physical sciences coursework. Consequently, the design course does not require students to perform complex calculations. This is done on purpose. As discussed above, engineering students at many universities must complete a freshman year curriculum of core math and science courses, often before taking their first formal engineering course. Consequently, they are forced to wait a year before learning from engineers what engineering is about. The freshman design course is meant to introduce students to engineering design thinking and to a set of qualitative concepts that are core to basic engineering practices, without the perquisite math and science training, with the goals of developing in students a motivation to study engineering, framing a context for later core engineering courses and helping to establish the relevance of the math and science curriculum to engineering practice. This happens as a consequence of the PBL approach, where students encounter problems that sometimes require math, science and engineering knowledge that they do not yet possess. Solving the design problems becomes a motivator for self-learning during the course and lends relevance to learning done after the course.

Development of an Assessment Survey

The above approach to design education raises several problems for quantitatively assessing student outcome achievement and the effectiveness of the course, since students do not yet possess enough technical/theoretical knowledge to do detailed design calculations (though they do perform some more basic calculations). Measures for formative assessment and assignment of student grades have been discussed above. In this section, we discuss a survey instrument that is being developed as a form of summative assessment that will be used to measure the overall effectiveness of the course. Detailed discussions of the student attributes we intend to measure and the development plan for the survey have already been presented elsewhere (Khalaf *et al.,* 2010). Here, we report on our most recent efforts to assess certain design thinking affinities such as problem solving, teaming, and communication, as part of an ongoing improvement process.

To briefly summarize the survey design, the survey is designed to measure the degree to which students possess expert-like attitudes toward engineering design. The motivation for measuring attitudes rather than skills is two-fold. First, such an instrument is currently missing from the engineering education literature but there is a clear need for it (e.g. Reed-Rhodes & Imbrie 2008). Second, measuring student attitudes should not be hindered by a lack of technical engineering knowledge, making it an attractive measure of course effectiveness for freshman students. The measurement target of the survey is conveniently described in terms of 3 core dimensions (see Table 1 in Khalaf *et al.* 2010). Each of the dimensions; (1) problem-solving, (2) teamwork, and (3) communication, are probed by asking students to register their agreement or disagreement on a 5-point Likert scale (strongly agree, agree, neutral, disagree, strongly disagree) with statements that describe an example behavior or belief. This question format for the survey is inspired by similar attitudes instruments in physics education, such as the Maryland Physics Expectations (MPEX) Survey (Reddish *et al.*, 1998), the Views About Science Survey (VASS) (Halloun, 1997), the Epistemological Beliefs Assessment for Physical Science (EBAPS) (Elby, 1998), and the Colorado Learning Attitudes About Science Survey (CLASS) (Adams *et al.*, 2006). The current version of the design course survey contains a total of 24 statements, representing each dimension with 8 statements. As an example, one statement from the "teamwork" dimension reads, "*A good team leader is democratic and invites collaboration.*" In this statement, the subject (the team leader) is doing something, in this case, inviting collaboration. By agreeing to the statement, the student is sanctioning the behavior, and vice versa if they disagree. Another example is "*It is important to inform my client or my team leader that their requirement cannot be met*". There is a wide variety of statements on the survey, drawn from principles concerning the steps of the design cycle, modeling and prototyping practices, client communication, teamwork dynamics, and more. The survey is also designed to be taken by students twice, once before and once after taking the freshmen design course, so that gains in favorable aptitudes and attitudes can be analyzed based on pre-/post- test scores. To maximize the utility of the design course survey in this capacity, statements have been carefully worded to avoid as much professional engineering jargon as possible, so as to make it conceptually accessible to freshmen students who may yet have no exposure to engineering concepts. This makes the design course survey very different from a standard end-of-course/instructor evaluation and potentially much more informative. As in the case of CLASS survey data, we anticipate student attitudes to be an important factor having a causal role in *determining the degree to which they adopt preferable (or "expert"-like) practices (*Perkins *et al.*, 2004).

Survey Validity and Reliability Study

As discussed by these authors (Khalaf *et al.* 2010) the first step for establishing the survey's test validity was taken during its creation. More than 100 candidate statements about engineering design were generated and each author here separately completed a categorization and a ranking task, attempting to sort the statements into the three dimensions of student traits intended for measurement, as mentioned above, and to rank them in terms of how relevant they were to the central features of that student trait. When the authors met and compared their choices for membership, a high degree of overlap was found within each dimension and a high degree of agreement was found in the statement rankings, suggesting some basic initial test validity. The 8 top-ranked statements from each dimension was chosen to form the pilot version of the survey and careful attention was given to wording so that the favorable response was randomized between "strongly agree" or "strongly disagree" responses.

As a second step in establishing the survey's test validity, we administered it to 25 professional engineers in the US during the summer of 2010. The goal was to see the degree to which these authors' choices of "favorable" responses to survey items correspond to the answers given by professional engineers. A strong correspondence further indicates test validity under the assumption that the aptitudes and attitudes that best serve professionals for their success in the workplace are those we should try to impart early to our students. Their responses to the 8 survey statements in

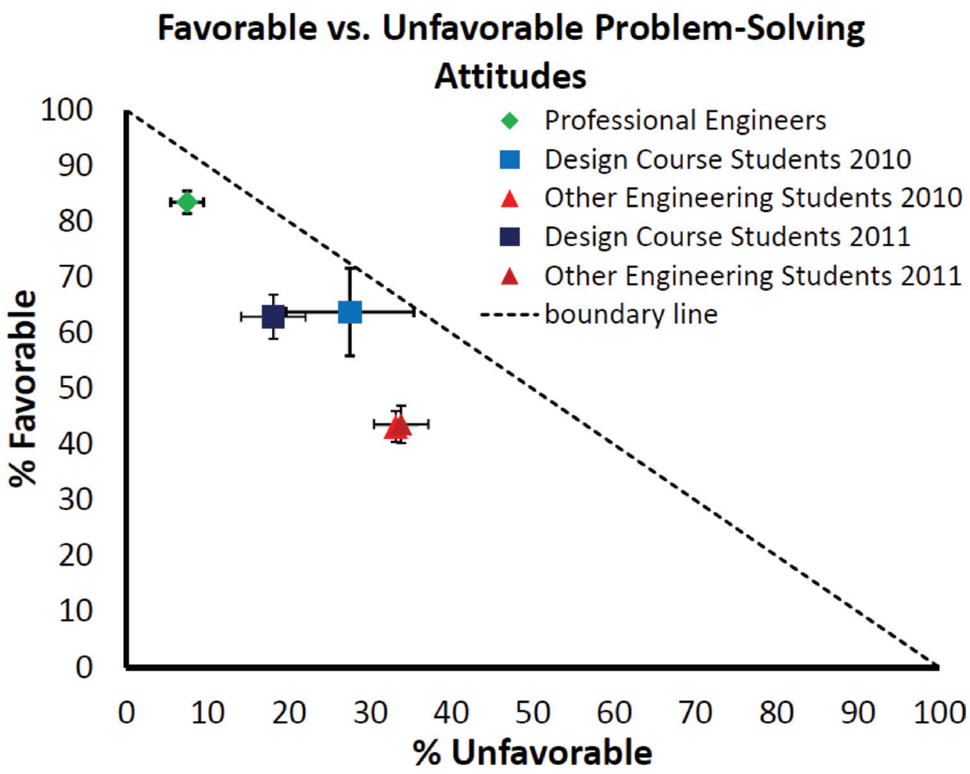

Figure 7. Favorable Vs. Unfavorable Plot For The 8 Statement Problem-Solving Section Of The Survey. Favorable Score (%) Is The Percentage Of Statements Where Respondents Answered As The Survey Creators Would, And Vice Versa For Unfavorable Score (%). No Score Assigned To Neutral Or Blank Responses Which Is Why The Two Scores Do Not Sum To 100% And Therefore Fall Below The Diagonal Boundary Line. Scores Are An Average For Each Group Surveyed; Professional Engineers (Blue Diamond), Students Who Have Taken The Freshman Design Course (Red Squares), And Students Who Have Not Taken The Course (Green Triangles).

the problem-solving dimension are shown in Figure 7 alongside the responses of two generations of Khalifa University freshman design course students and two year groups of Khalifa University engineering majors, in a “favorable/unfavorable” plot, as is done with the MPEX survey (Reddish *et al.*, 1998). All students surveyed are engineering majors. The “design course students” are those engineering students who have taken the freshman design course. The “other engineering students” are freshman engineering majors who have not taken the freshman design course.

As in the example teamwork statements given above, the authors’ choice for the “favorable” response was either “strongly agree” or “agree” and therefore “unfavorable” scores were given to the disagreeing responses. As done by Reddish *et al.* (1998) for the favorable-unfavorable plot, neutral responses or non-responses on survey items were left unscored so that the plot reveals the 'polarization' of opinion in the population. "Strongly agree" and "agree" responses are merged, as are "strongly disagree" and "disagree", due to limited statistics. The percentage (%) favorable and percentage (%) unfavorable score was then calculated for each respondent and plotted in Figure 7. Those respondents who answer all survey items and answer as these authors would on all statements (agree or disagree), are scored 100% favorable, 0% unfavorable, and so would appear in the upper left-hand side of the plot. Our respondent groups; professional engineers, students who had taken the freshmen design course (and who are surveyed post-instruction), and students who had not taken the course, are represented in Figure 7 with blue diamonds, red squares, and green triangles respectively. Scores are plotted for the group averages and error bars represent standard error in the average ($\sigma/\sqrt{N}$). The black boundary line connecting the upper left and lower right corners represent the maximum possible sum (100%) of favorable and unfavorable scores. All scores will then fall somewhere along this line or below this line, if there are neutral or blank responses.

Observations on the Survey Data

First, we clearly see that professional engineers scored the most favorably of the three groups on the survey overall. This is a positive indication of the survey's test validity; we sought to measure basic concepts in engineering problem-solving and there is some agreement about what are the "favorable" stances. More importantly, we also see that students who have taken the design course are on average 20 ± 5% closer to the professionals' score than students who have not. This suggests that the design course has a positive impact on these students, in terms of gearing their design thinking skills and shaping their beliefs about basic engineering problem-solving practices to be more like those of expert professional engineers. We also see evidence of good external reliability for the problem-solving survey, as successive classes of students are consistent with one another; the average response of design students surveyed in 2010 and 2011 are consistent with each other, as are non-design students surveyed in the same years.

Regarding the survey's internal reliability, we have calculated Cronbach's α-scores for the 8 statements of the problem-solving portion of the survey, as shown in Table 3. There is clearly room for improvement and the pattern of scores over the subject populations hints at two possible issues for focusing future efforts; (1) general English language understanding and (2) engineering jargon usage in survey statements. From the professional engineers' perspective, the problem-solving portion of the survey appears to clearly measure a coherent cognitive construct ($\alpha = 0.87$). However, the less initiated into engineering design the subject population (design course students post-instruction, then all other engineering students, respectively), the lower the Cronbach's α-scores. But this is

Subject Population	Population Sizes	Cronbach's α-Scores
Professional Engineers	$N = 25$	0.87
Design Course Students	$N = 34$	0.76
Other Engineering Students	$N = 109$	0.72

Table 3: Population Sizes And Cronbach's α-Scores For The Design Problem-Solving Survey.

also the sequence that would likely represent the level of initiation into the English language. All the professional engineers surveyed speak English as their mother tongue. The design course students have typically undergone one year of engineering education in English, and the non-design students none. This suggests that the wording or vocabulary usage in the statements are such that the professional engineers *'know what we mean'*, or understand better what we *intend* to ask, but the students may not.

Outlook for the Survey Development

Once the survey is further refined, more sophisticated analyses (e.g. correlation studies with teaching practices, demographics, etc.) will give instructors a quantitative measure of their teaching effectiveness and help them further develop concrete goals and effective methodology for the design course. For example, Figure 7 shows the favorable/unfavorable plot for just the 8 problem-solving statements, showing a similar pattern but a greater level of agreement with professionals. Important information can be gained from examining individual dimensions of the survey, similar to the design and analysis done with MPEX survey (Reddish *et al.*, 1998) in physics education which is an inspiration for our survey. Research with the MPEX instrument found that while introductory physics instruction had positive effects on student appreciation of the relevance of physics, some teaching practices actually had a negative impact on their self-efficacy, an important consideration in long-term retention of physics majors. A similar study examining the impact of design education on student self-efficacy for engineering majors could lend valuable insights for improving both the effectiveness of pedagogy and retention of students within engineering disciplines.

There are still significant steps that need to be taken to validate the design problem-solving survey. At present, there is no data to perform a proper pre-/post-test gain analysis, as logistical issues have prevented design students from being surveyed pre-instruction. The design students and non-design students compared here are not the same students, so one can argue that we cannot be absolutely certain that the course has had a positive effect on the design students. Rather, they simply form a sub-group of entering freshmen engineering majors that knew more about engineering or who had more favorable problem-solving attitudes than their peers did. Since students have some flexibility (first semester or second semester freshman year) for choosing when to take the engineering design course, our result presented here could be just the result of a selection bias on this population, singled out by their understandable choice (due to their prior affinity) to take the course earlier than the other students. Further survey data of professional and academic engineers, to further refine the target of the survey and more clearly define what is and is not a favorable from an expert perspective, is also necessary. This is prompted by the fact that these authors' agreement with the professional engineers polled is on the level of 75%-85%, whereas 90% or greater would be more satisfactory.

Furthermore, as we seek to improve the internal reliability and raise the Cronbach's **Đ**-scores for all population groups, we must determine if the survey statements need to be clarified in terms of their basic English usage or in terms of their engineering jargon usage (or both). Both kinds of improvements are necessary to accomplish our goal that the survey be used pre- and post- instruction on our freshman students and, therefore, on a group that has little or no formal knowledge of engineering and only a basic working knowledge of English. We plan to address both issues by conducting detailed interviews with future respondents and studying their open-ended feedback about the survey statements to search for words or phrases they find ambiguous.

COURSE IMPACT ON DESIGN THINKING AND DESIGN PERFORMANCE

There is convincing evidence that the pedagogical approach, specifically the course's emphasis on students' use of a prescriptive design cycle, has a positive impact on teams' design demonstration performances. To elaborate, two metrics, the normalized design demonstration score S_D and the normalized design report score S_R, are compared. For both metrics, the normalization is done relative to the maximum possible score for each respective project. Design reports were graded on the degree to which the team had followed the course's prescribed design cycle and the quality with which they had elaborated on the each of the cycle's steps (see e.g. "Case Study: Design of a Deployable Cantilever Beam" above). Table 4 shows content criteria for determining S_R that is common to all five projects in the course. Design demonstrations were judged using metrics to determine the degree to which a design satisfied client objectives and constraints. For the "Deployable Cantilever Beam" project described above, scoring metrics were 1) arm deflection from target and 2) system reliability (consistent performance over repeated use). Designs were disqualified from the demonstration for failure to meet the constraints. For the Cantilever project, this was failure to meet the system volume and 4-point wall contact constraints.

Design Report Components	Weight
Going through the prescriptive 5-stage design process, indentify the input, tasks and output of each stage.	25
Clearly present the Objective Tree similar to Figures 3.1 and 3.2 (Dym & Little 2003).	10
A pair-wise comparison chart similar to Tables 3.2–3.4 (Dym & Little 2003)	10
Construct your revised project statement	15
Identify the constraints for your design	5
You have to present your alternatives using feee-hand or computer sketches that show at least 3 alternative designs	15
Present all of your work in a report format	20

Table 4: Example Content Criteria For Student Design Reports. Some Special Content Items, Related To Project Management, Were Added For Later Projects, But All Reports Contained These Measures Of Design Cycle Knowledge In Common And Gave Them Similar Relative Weights In The Design Report Score S_R.

Adherence to the prescribed design cycle, as measured by S_R, is significantly correlated with a team's design demonstration performance S_D by the end of the course. Over the course of the semester, student teams tackle five major projects in total which are indicated in chronological order across the horizontal axis of Figure 8. In general, the difficulty of projects grew substantially across the sequence, as problem statements were written more ill-posed, design spaces were made larger with the introduction of novel tools and components, and instructor scaffolding and coaching were increasingly withheld. Figure 8a (top panel), shows the average of the design demonstration performance scores S_D, normalized to 1 for the purpose of comparison. Errors shown are standard errors in the mean ($\sigma/\sqrt{N}$), taken over the six student teams in the population. Figure 8b (bottom panel), shows the Pearson's population correlation coefficient ρ between the set of design report scores and design demonstration scores. Errors shown are standard errors in the ρ coefficient ($(1-\rho^2)^2/\sqrt{(N-1)}$).

For the final project, the correlation ρ is moderate-to-strong ($\rho(S_R, S_D) \sim 0.66$) and significantly differs from zero with >90% confidence (*two-tailed t-test*). Interpreting the emergence of this correlation as that of greater design knowledge *causing* improved design performance is certainly plausible but, strictly speaking, premature. Alternative explanations, such as a growing, general academic ability or personal maturity amongst the students, or other such factors cannot be eliminated from consideration as causal factors. Nevertheless, the positive pattern observed in Figure 8 over the span of the course is significant and encouraging. It is clear that improved design knowledge in the students and their improved design performance become connected as the semester progresses, as problem ambiguity and design space size increases and the project difficulty grows.

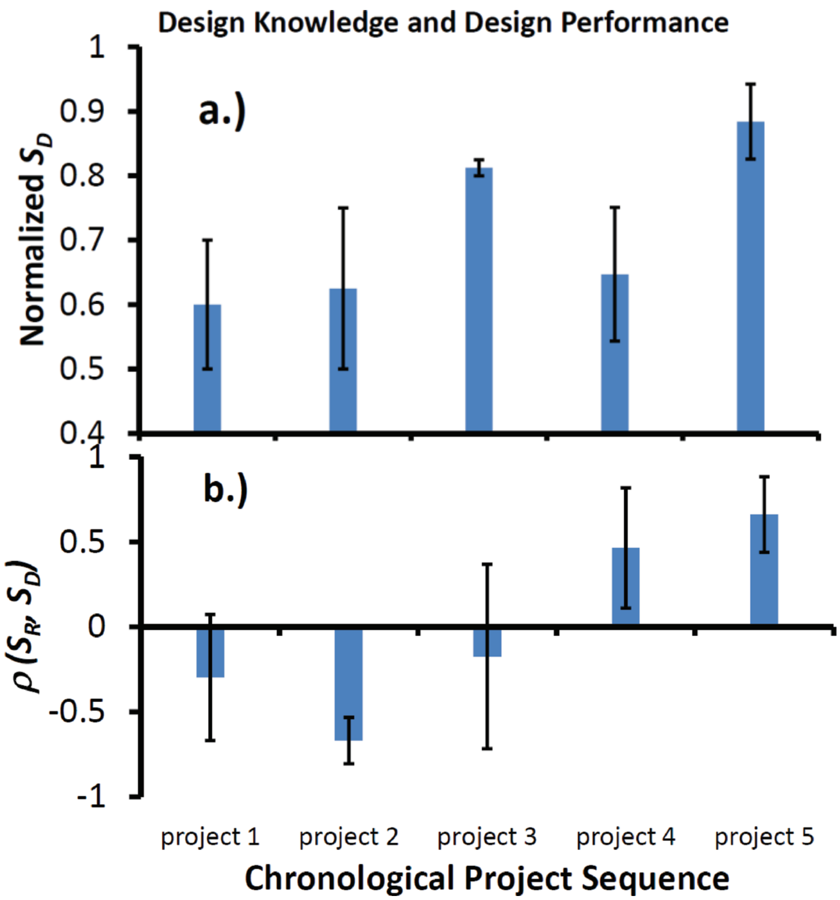

Figure 8. Emerging Correlation r In The Student Population, Between Design Demonstration Performance SD And A Measure S_R Of Their Adherence To The Course's Prescribed Design Cycle As Shown On Design Reports.

There is anecdotal evidence that the introduction of certain design techniques do have a direct influence on the correlations in Figure 8 as well. Starting just prior to project 3, students were introduced to and encouraged to follow good project management techniques, including the use of Gantt charts, responsibility tables, etc., as described by Dym & Little (Dym & Little, 2003). Prior to this, some teams preferred to begin prototyping and building immediately and did not see the benefit of working through design cycle activities like objective trees and pair wise comparison charts. Some teams managed to achieve a better demonstration score than other teams due to the simpler nature of early 1-3-week projects which is seen clearly in Figure 8 for projects 1 & 2. Here, variations between teams' demonstration scores are the largest, suggesting that other factors are largely determining demonstration success. For the more demanding, 4-5 week projects later in the course, these approaches of skipping parts of the design cycle and relying on tinkering made it very difficult for teams to converge on a single, promising design from within these projects' larger design spaces. The inability to converge and reach consensus within the team was often a driver for them to return to the design cycle and redo their analysis of the client problem statement, to get newly emergent questions answered by the client, and attempt to converge on a final design again, going through the prescribed cycle. The difficult nature of later projects also require better time management skills since these projects (most notably 4 & 5) require students to design parts with CAD software (Pro-E) and submit them in a 4-5 week time frame for printing on the 3D rapid prototyping printer in a machine-shop style queue. On project 5, students are required to plan and show responsibilities using Gantt charts, work breakdown structures and linear responsibility charts which are incorporated into the design report components shown in Table 4. The moderate-to-strong correlation between this report and the associated demonstration performance (and the lack thereof on previous projects) suggest that following the prescribed design cycle may only have a strong influence on the quality of the finished design when the project is of a sufficient difficulty. On simpler projects, the design cycle can be 'short-cut' with tinkering and ad-hoc solutions without necessarily having a negative impact on the finished design.

CONCLUSIONS

This paper presents ongoing work to develop, implement, and assess the impact of an innovative, interdisciplinary, engineering design-and-build course towards improvement in engineering design education at three different levels of placement, content, and pedagogy. The course, which is infused at the freshman level, aims to promote expert systematic design thinking and culture using an inductive, problem-based learning method, PBL, as the mode of delivery.

Towards this goal, the design course is structured to actively engage the students in the various phases of a prescriptive design-and-build cycle (problem formulation, conceptual design, preliminary and detailed design, rapid prototyping, interface and control programming, and design communication) using ill-structured, open-ended problems inspired from industry. The student teams have access to various tools including a LEGO Mindstorms robotics kit, a C++ programming interface, and a 3-D prototyping printer. Further goals besides developing the students' design thinking and problem solving skills, include the enhancement of their "soft' skills in response to ABET criteria such as communication, teaming, as well as global and social awareness impact skills.

One of the main contributions of this work is the unique integration of the prescriptive design cycle with problem based learning (PBL) to promote effective inquiry and the systematic iterative interplay between divergent and convergent questioning in engineering design education. The inherent alignment between PBL and expert design thinking process allows students to tackle complex problems by following an iterative loop of divergent-convergent thinking and decision making to reach an optimal solution. Evidence presented shows an emerging connection between 1) a team's ability to follow and iterate on the prescribed design cycle and 2) the performance of a team's finished design. This connection is driven, in part, by the difficulty of the project. As a result of this mode of instruction, students also develop more expert-like attitudes toward design problem-solving, relative to other engineering students. Work is ongoing to address particular challenges encountered, such as effective team formation and individual student accountability within teams.

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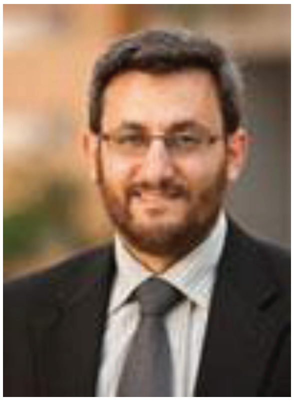

Shadi Balawi earned his PhD degree from University of Cincinnati in 2007 in Aerospace Engineering with research focus on experimental design and testing of solids and structures especially the aluminum honeycomb core materials. Prior to him joining University of Cincinnati, he earned his Bachelor and Master degrees from Jordan University of Science and Technology where his research was in the areas of experimental heat transfer. Dr. Balawi had taught courses in materials, design and heat transfer at both University of Cincinnati and University of South Carolina in Columbia- SC. He also taught courses in engineering measurements, mechanical systems design, aircraft structures and engineering problem solving at American University of Sharjah and Khalifa University of Science and Technology and Research for both graduate and undergraduate students. He is actively engaged in research of freshman design thinking education.

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Ahmad Radaideh received the B.Sc. degree in Computer Engineering from Jordan University of Science and Technology, Jordan, in 2005, and M.Sc in Computer Security from The University of Birmingham, UK, in 2008. Currently, he is a lab instructor with Electronic and Computer Engineering Department, Khalifa University, Abu Dhabi, UAE. His research interests include education, software security, data security and enterprise rights management"