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A Review of Outcome-Based Education and the Use of Engineering Design Competitions to Improve Underrepresented Attributes*

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Engineering as a profession is becoming increasingly complex and competitive. New technologies (advanced telecommunications and computer-aided engineering), and reduced barriers to international trade have allowed corporations to move engineering activities into emerging economies. These factors have allowed corporations to "unlock" traditional forms of organizational integration and undergraduate engineering programs in universities in these developing countries are quickly approaching the quality of programs in western countries, vastly increasing the pool of engineers from which companies can draw. The reduced cost of operation in these emerging economies has put pressure on western countries to produce engineers that can encourage companies to keep high quality, technical engineering jobs local, instead of outsourcing. This raises the question: what are the attributes of a high-quality engineer, and what changes to the engineering curriculum need to occur to emphasize these attributes? In this paper, we examined the history of modern engineering education and the push toward an outcome based evaluation of graduate skills. We identified which where the most important graduate outcomes in engineering practice, and outlined how engineering design project courses can be used to emphasize these attributes. Engineering design competitions were highlighted as an ideal source for projects when coupled with the teaching techniques of problem based learning (PBL) and cooperative learning (CL).

Keywords: engineering design education; globalization; graduate attributes; problem based learning; cooperative learning; engineering design competitions

1. Background

The modern profession of engineering has existed from the mid 1800's. From its early roots as a purely military profession (*engine'er*), societal demands for infrastructure such as roads, bridges and buildings led to the creation civilian focused (civil) engineering profession [1]. This was the beginning a continuing trend toward specialization as a boom of new technologies were introduced during the so called Second Industrial Revolution, during which specializations such as mechanical, chemical and electrical engineering were introduced. Early engineering education was largely focused on teaching the skills needed to *practice* engineering [2]. After WWII, President Roosevelt asked the Office of Scientific Research and Development what could be done to disseminate the scientific knowledge developed during the war, as well as aid future research activities. The response [3] led to the creation National Science Foundation, and a fundamental shift in the nature of engineering education from *practice* to a focus on engineering science and research. Early analysis of engineering education, such as the prestigious Grinter Report [4], called for a "strengthening of work in the basic sciences", and "identification and inclusion of six engineering science". The report also called for the curricula to contain "an integrated study of engineering analysis, design, and engineering systems", a "concentrated effort to strengthen and integrate work in the humanistic and social sciences", "an insistence upon the development of a high level of performance in the oral, written, and graphical communication of ideas" and "the encouragement of experiments in all areas of engineering education", however these elements were not nearly as emphasized in curricula as the engineering science elements [5]. As the first post-war engineering Ph.D.'s graduated and entered academia, the emphasis on research and engineering science became more entrenched [6]. This has led to decades of engineering graduates that are excellent *scientists*, but lack design, analysis and professional skills [6–8].

2. Assessing methodologies

2.1 Graduate attributes

In 1971, ABET, the regulatory body that accredits engineering programs in the United States, identified the issues of poor design related content in the curriculum and attempted to heavily increase the amount of design activities required to receive accreditation [7]. Poor uptake and enforcement by school led to a retraction of these increases [7].

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Table 1. Approximate graduate attribute equivalencies

ABET		CEAB		IEA	
3a	Knowledge	1	Knowledge	WA1	Engineering Knowledge
3b	Experiments	3	Investigation	WA4	Investigation
3c	Design	4	Design	WA3	Design
3d	Teamwork	6	Teamwork	WA9/WA6	Teamwork The Engineer and Society
3e	Solve Problems	2	Problem Analysis	WA2	Problem Analysis
3f	Ethics and Professionalism	10	Ethics and Equity	WA8	Ethics
3g	Communication	7	Communication	WA10	Communication
3h	Impact	9	Impact	WA7	Environment and Sustainability
3i	Lifelong Learning	12	Lifelong Learning	WA12	Lifelong Learning
3j	Contemporary Issues	8	Professionalism	WA6	The Engineer and Society
3k	Engineering Tools	5	Engineering Tools	WA5	Modern Tool Usage

Modern accreditation procedures are now outcome-based; focusing on what is learned, rather than what is taught [9–12]. ABET's EC2000 accreditation procedure [13], as well as the International Engineering Alliance's (IEA) Washington Accord [12] and the Canadian Engineering Accreditation Board (CEAB) [14] all have a list of graduate attributes or outcomes that define the expected capability of graduates. An approximate equivalency between the graduate outcomes is shown in Table 1 [10]. An outcome-based accreditation procedure has allowed universities more freedom in curriculum development, particularly in the relative emphasis that they place on the specific outcomes [15].

Determining which graduate outcomes are most important has been the subject of much research [2, 7, 15– 21]. Students and employers expect that the importance of graduate competencies should align with the competencies required for professional practice [15]. Many surveys have been published, asking employers and graduates to rate which attributes are the most important. Comparing and contrasting these surveys in order to get an overall look at which outcomes are the most important is difficult for many reasons. First, the importance of outcomes can vary greatly depending on the academic discipline. For example, industrial engineers and manufacturing engineers have been shown to have significantly different rankings of graduate attributes [21]. Similarly, the work environment influences which attributes are ranked highly. Finally, the results of these surveys change depending on the wording used [15]. When asked to rate each attribute, respondents gave different results compared to when they were asked to choose the most important attribute [21]. Passow attempted to normalise these factors in an extensive, seven-year study in which over 4000 recent graduates were surveyed and asked to rate how important each of the ABET competencies were in their professional experience. The results showed a clear cluster of top rated competencies which were Teamwork, Communication, Data Analysis and Problem-Solving [15].

2.2 Taxonomies of learning

While the learning outcomes set by ABET, CEAB or IEA describe the general ideas and skills that students should have acquired during their education, determining how well, or to which level the students have the outcomes is also of importance. Continuous improvement of the curriculum and ensuring that the important outcomes are emphasized is of great importance [15]. One of the most common and widely applied techniques for evaluating the quality of learning is Bloom's Taxonomy [22]. Bloom's original work in 1956 [23] outlined a hierarchy of the level of quality of the students' responses. The six levels he described were: Knowledge (rote production), Comprehension, Application, Analysis, Synthesis and Evaluation. This original taxonomy was useful, but primarily for the creation of test questions, rather than an evaluation of outcomes. In 2001, Anderson & Krathwohl [24] updated Bloom's taxonomy to address some of the shortcomings of the original Taxonomy. The new taxonomy revised the cognitive process to be: Remember, Understand, Apply, Analyse, Evaluate and Create. Additionally, it added a second dimension to the taxonomy to describe the different knowledge types, which they labeled as: Factual, Conceptual, Procedural and Metacognitive. This creates a 24-cell grid which both describes the intended cognitive process and the category of knowledge of the intended attribute, outcome or task. While this evaluation technique is widely used [25], there have been some questions as to how effective it is when applied to open ended problems, as well as how reliant it is on the direct link between evaluation questions and answers [26]. Additionally, while the higher levels of Bloom's taxonomy are undoubtedly higher levels of understanding, it is possible to achieve the higher levels in Bloom's cognition scale without achieving all or some of the lower levels [22]. An alternative to Bloom's taxonomy is Bigg's and Collin's Structure of the Observed Learning Outcome (SOLO) Taxonomy [26]. The SOLO taxonomy is structured analogous to Piaget's developmental cycle and represents an irreversible sequence of cognitive progression; i.e. "SOLO describes a hierarchy where each partial construction [level] becomes a foundation on which further learning is built" [27]. The SOLO taxonomy consists of five levels:

Level 1: Prestructural.
Level 2: Unistructural.
Level 3: Multistructural.
Level 4: Relational.
Level 5: Extended Abstract.

At the prestructural stage, which is often considered outside of the taxonomy, students have little understanding of the subject, or miss the meaning all together. As a student learns, the complexity of their knowledge undergoes two main changes. In the unistructural and multistructural levels, the changes are quantitative, i.e. the amount of detail in the students understanding increases. During the relational and extended abstract levels, the change is qualitative which means that the students' knowledge is then integrated into an increasingly complex structural pattern. Often, verbs are assigned to different learning levels in order to guide teaching and the assessment of learning outcomes (see Fig. 1).

These verbs can be used to help identify how well learning objectives have been met, and are often used by universities to help evaluate their curriculum. One advantage of the SOLO taxonomy is that a student cannot proceed to a higher level without having achieved the previous level, outlining a clear progression of learning in the student [26].

3. Improving outcomes through design projects

3.1 Design projects

Industry has made it clear that it values *designers* more than *scientists* [7, 28]. For many years, the engineering design curriculum consisted of a final year Capstone design course. These courses were created to meet the graduate outcomes design requirements [8]. In response to the apparent disconnect that first and second year engineering students were feeling from engineering practice, additional courses in design, commonly called cornerstone design courses, were implemented [8]. There have been several initiatives to improve the relative emphasis of the design curriculum. WSU's Transferable Integrated Design Engineering Education (TIDEE) program [29], and MIT's Conceive-Design-Implement-Operate (CDIO) [30] are examples of attempts to focus and improve the design related aspects of the curriculum. In Canada, the Natural Sciences and Engineering Research Coun-

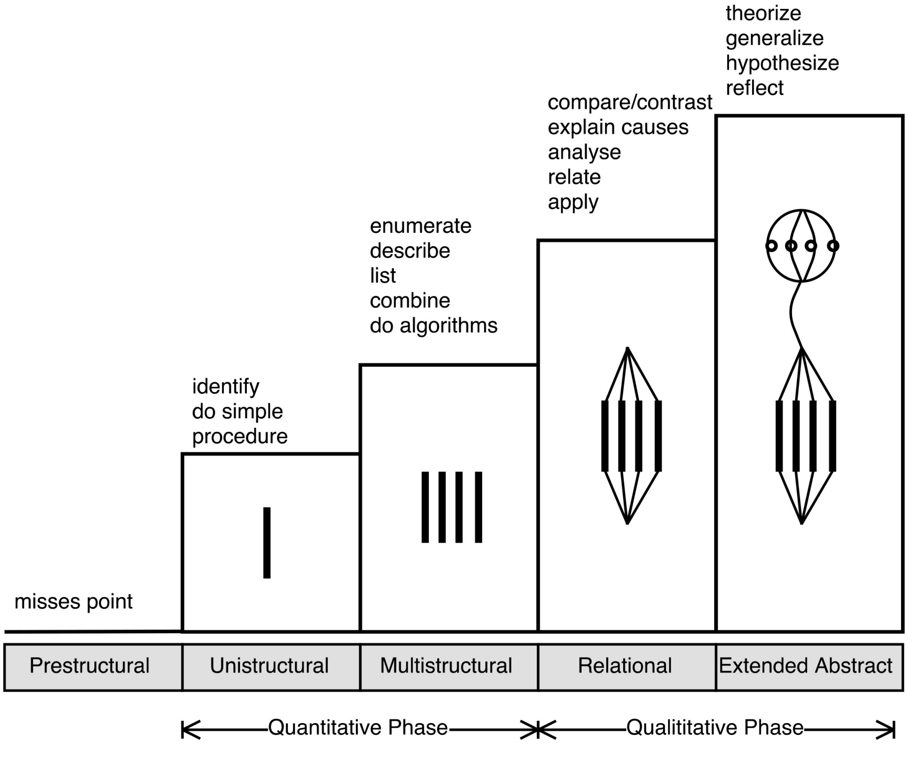

Fig. 1. The SOLO taxonomy with descriptive verbs [26].

cil of Canada (NSERC) Chairs in Design Engineering/ Environmental Design Engineering (CDE/ CEDE) program was established to improve the level and quality of design engineering activity within Canadian Universities [31].

Capstone Design courses take the form of large scale— often multidisciplinary—team design project during a students' final year of study. Students at this point in their academic career have a wide range of theoretical knowledge, as well as engineering tools at their disposal. This allows these projects to be complex and gives students the opportunity to solve real-world problems, often sourced from community or industry partners.

Thompson [32] proposes that Cornerstone Design courses can be roughly classified into three groups. First, are courses that teach engineering skills related to design, such as CAD, machining, drawing, etc. The second group consists of a semester-long design project where students are introduced to the design process. The third group contains elements of the first two groups where various aspects of design and engineering are introduced through small hands-on projects or exercises, such as reverse engineering. 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 [8, 33].

Design may not be at the top of the list attributes that engineers cite as most important in their professional careers [15], but this may be due to the variety of professional positions that engineers occupy, some of which may not directly contain elements of design. Design courses however, particularly project based design courses, are excellent methods of teaching and developing the top ranked attributes: teamwork, communication and problem solving. Ultimately, the goal of these projects is to move students to higher levels of understanding or skill within these attributes, and do so in a manner that reflects professional practice as closely as possible.

There are numerous variations of the engineering design process, each of which may be specifically suited to a specific task, discipline or corporate structure. Whatever the variation, they should all be an iterative process involving Problem Analysis, Conceptualization, Design, Testing and Analysis. Examples of a simple design process and a corporate focused design process is shown in Fig. 2.

3.2 Sources of design projects

Designing a project based design course has been the subject of much study, particularly since the introduction of the design focused graduate attributes. Finding an appropriate source for design projects is one of the most difficult aspects of creating a design course. From the literature [34], a design project should have the following characteristics:

- Be challenging.
- Ability to be completed within the scope of the course.
- Sufficiently understood and documented subject matter.
- Emphasize the application of theory.
- Make use of the engineering design process.

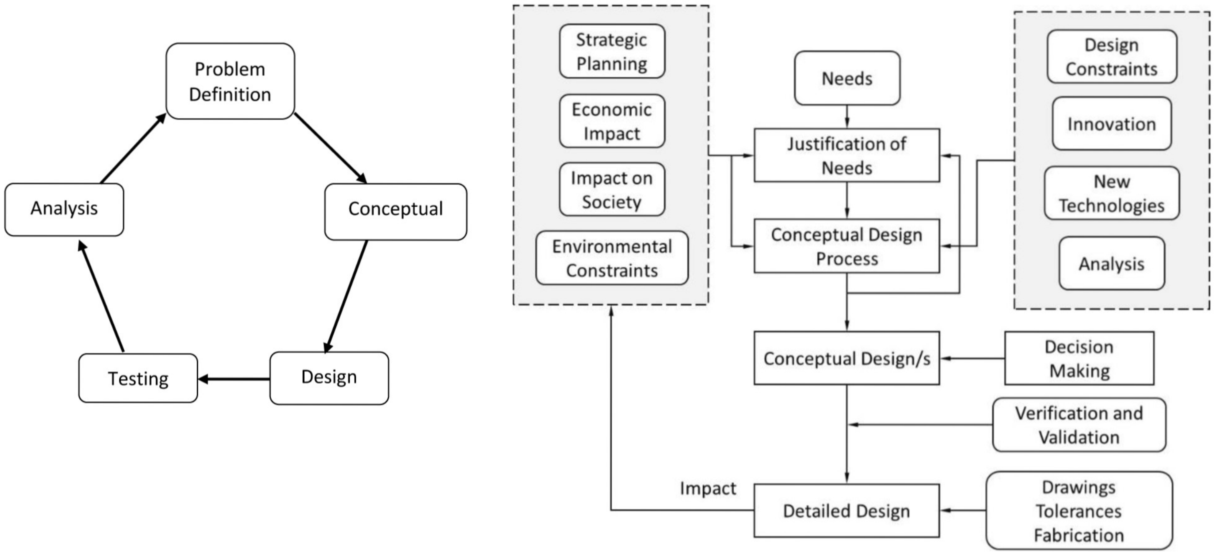

Fig. 2. An example simple and more complex engineering design process.

- Be subject to specifications, standards and safety criteria
- Not involve proprietary information (if industry is involved)

Five potential sources for design projects were identified by Dutson et al. [34]. These sources included:

- Hypothetical projects—Course directors make up a project, which can be tailored to have all of the required project characteristics, and emphasise any particular engineering or design element the instructor wishes.
- Student-selected projects—Students find their own projects as long as they meet the criteria set by the instructor.
- Research Related Projects—Professors propose design projects related to their research, for example, an experimental test apparatus.
- Industrial Sponsored Projects—Projects are solicited from industry to solve real world industrial problems.
- Engineering Design Competition Projects—Student design competitions sponsored by engineering societies or other technical bodies can provide well-structured projects.

One of the stated goals of improving engineering education is to expose students to real-world problems and situations [8, 35, 36]. Hypothetical projects, however carefully designed, remove one of the key factors of a real-world problem which is stakeholders. Stakeholders, be it a company who wishes to create a valuable product, or an end user with specific needs and goals are very important. Stakeholders are rich sources of background and ancillary information that is not captured in an initial problem definition or specification list, and play a large role in elevating a project from an exercise to a real-world simulation. Research related projects can suffer similar disconnects from real-world problems simply due to the nature of research conducted at universities which, as stated earlier, tend to be heavily focused on engineering sciences rather than real-world problems.

Student-selected problems carry with them difficulties, particularly with regards to the burden placed on the instructor to ensure that the project will meet all of the requirements of a good project [34]. Students, particularly when the course is aimed at first or second year students (cornerstone design courses), have poor sense of the scope of projects, and can choose projects that are either too difficult and will require more than the allotted time for the course, or projects that are too simple, and do not provide adequate challenge. Additionally, the variability in the challenge of the projects will lead to difficulty in the relative evaluation of student teams' marks at the end of the project.

Industrial projects offer the best opportunity for introducing a real-world problem to students. Students can be highly motivated by these projects as they can see the real application of their project. The major difficulty with industrial led projects is coordination. Finding a sufficient number of industrial projects that can meet all of the requirements for the course can be a monumental undertaking. Second, companies will often have a timeline for their project that can vary greatly from the course. Ownership of anything created by the student teams needs to be clearly defined at the start of the industrial partnership, and these ownership agreements can discourage some companies from taking part. Changes in project scope and direction can occur at any point in an industrial project due to the myriad of forces that a company is under, which can lead to students without a project partner part of the way through the course.

Engineering design competition projects offer the best compromise between a manageable design experience and that of a real-world project. While the goal of these competitions is different than that of an industrial project (to produce a product or process to sell or incorporate into their production), the outcome is still the same; produce a functioning design that must be able to compete against competitors' designs.

3.3 Engineering design competitions

Engineering Design Competition events have been had a long standing, and highly successful presence as extracurricular activities for students for decades. The most commonly found events at universities are SAE International's Collegiate Design Series which includes events such as Formula SAE, Baja SAE, SAE Aero Design, SAE Clean Snowmobile and SAE Supermilage [37]. Other similar design events are held by other organizations, such as NASA's Centennial Challenge series [38] and ASCE's Concrete Canoe Competition [39]. As these projects are all complex, and similar to real world engineering projects. They are inherently multidisciplinary; they draw upon the engineering knowledge base of all of the major disciplines, from mechanical and electrical, to civil and chemical engineering. In each of these competitions, the goals, constraints and safety regulations of the project are clearly outlined to the students. In general, the design competitions occur once per year, usually shortly after the completion of the winter semester (June–July), and teams must submit a new entry every year, meaning teams have approximately 9–12 months to complete their design depending on how active teams are during the summer semester. Student teams for these

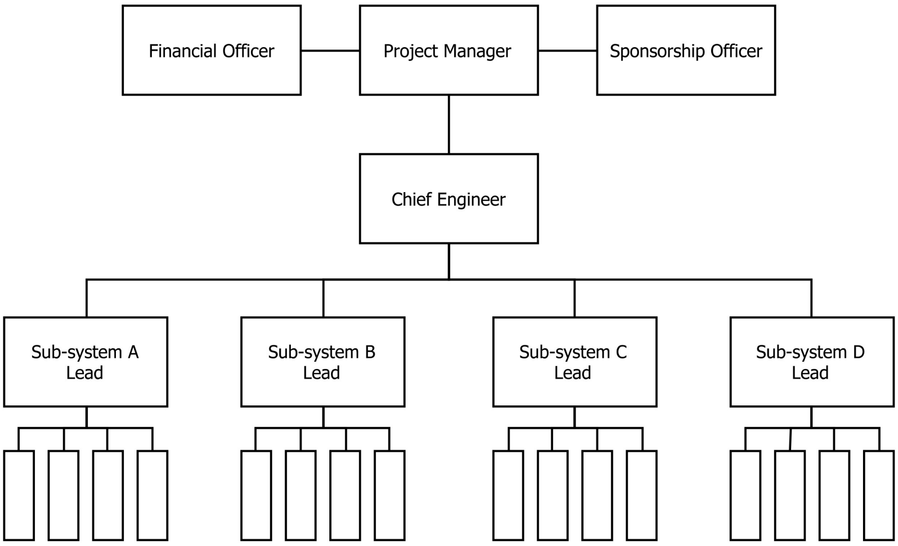

Fig. 3. Hypothetical organizational structure for student engineering design competition team.

competitions operate as a small business, often with a structured hierarchy and management system in which experienced team members take the role of upper management, and new members, which often have to go through an interview process, take the role of interns, or new hires. Fig. 3 shows a hypothetical organizational structure for a student team.

Under this structure, the chief engineer would be the most experienced member of the team, often an upper year student who has been a member of the team for several years. Their role would be to make high level design decisions, ensure integration between different subsystems, and oversee packaging. Each sub-system lead will report regularly to the chief engineer regarding any issues that will affect the overall design. The sub-system lead will be in charge of making design decisions, conducting analysis and simulation regarding their particularly sub-system, and they will have a team of lower level team-members who will make minor design decisions and manufacture components. The project manager will deal with the logistical needs of the team, liaise with sponsorship and financial officers, and handle any personnel issues. Students obtain funding for their projects through sponsorships with companies or other organizations and must manage their money in a professional manner, similar to a small business.

4. Pedagogy and learning theory

Kolb's experiential learning cycle [42] 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 (See Fig. 2) as a whole, where a product is designed, built, tested and analysed, 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.

Developing learning activities that can address all of the desired graduate outcomes, particularly the most important and under-represented attributes has been a topic of much study [8, 40]. Kolb's experiential learning cycle has been implemented into several pedagogical methods. One instructional method that has gained wide acceptance and aligns closely with engineering design projects is *problem-based learning* (PBL) [41, 43, 44]. PBL was developed originally in medical schools in order to prepare students for professional practice in the 1970's. Professional associations at the time questioned if traditional teaching practices were adequately training students to deal with the real-world problems seen in practice. In PBL, students take on the role as primary investigators in the problem-solving procedures. Students are allowed to progress through the process in a way that simulates the natural learning style of students (inductive rather than deductive, see Kolb [42]). According to Barrows [48] A PBL model consists of the following basic characteristics: (a) learning is student centred; (b) learning occurs in small groups; (c) teachers are facilitators or guides; (d) problems form the organizing focus and stimulus for learning; (e) problems are a vehicle for the development of problem-solving skills; and (f) new information is acquired through self-directed learning. The PBL process (iteratively) generally follows the following steps: (1) Define the problem, (2) Hypothesize solution methodologies, (3) List *what they know, what they need to know and what they need to do*, (4) Conduct research and analysis in order to update the *what they know* and *what they need to know* lists, (5) Propose solutions and assess their appropriateness, (6) critically reflect on the process used to generate a solution.

Another important instructional method being applied in engineering education is collaborative learning or Cooperative Learning (CL) [45]. In this method, students work in teams to achieve a common goal, and each student can only achieve their learning goal if the other members of the group achieve theirs. The most common model of CL is that of Johnson et al [46], which specifies 5 basic conditions under which the students must work: (1) *Positive Interdependence* (2) *Individual Accountability* (3) *Face-to-Face Promotive Interaction* (4) *Appropriate us of collaborative skills* (5) *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 [47].

5. Using engineering design competitions in the classroom

The structure of engineering design competition teams take aspects from both PBL and CL, even without the intervention from educators. That students naturally organize themselves into these structures emphasizes the natural learning aspect of these styles. The scope of the design project selected for use in the classroom will depend on which level of course (capstone or cornerstone) is being designed. For capstone projects, teams can be assigned at the subsystem level, where each team will be in charge of the complete design of one subsystem. Cornerstone courses should be assigned projects at with a smaller scope, such as the design of a component within a subsystem. The smaller scope projects will have necessarily have lower knowledge requirements, and be more well defined and therefore be less demanding in terms of design skill and team management. Project course teams can use the team member at a higher level in the proposed hierarchical tree as their primary contact and resource. This team member can be a part of the assessment and evaluation of the students' performance in addition to the course instructor similar to how liaisons from industrial sponsored projects work in other capstone courses [34].

5.1 Building effective design teams

Teamwork is often cited as the most desired outcome from team projects [49]. 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 [50–52], and there are several key behaviours that each of them attempts to promote.

The first behaviour encouraged is interdependence [49]. 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 [49]. 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. Additionally, students can be asked to complete a team policies and expectations contract (such as suggested by [53]). This contract can outline what was expected of each student when working in a team, such as communicating promptly and completing assigned work on time. The contract can also contain a policy for dealing with social loafing or uncooperative members within teams. Students should be encouraged to modify or add policies at their own discretion. Through feedback from students, we have found that the contract ensures that all students understand the policies set out by the course, and gives them a sense of ownership over the performance of their team.

The most cited and common complaint from students when working is teams is the concept of social loafing [49]. 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. We have found that the Comprehensive Assessment of Team-Member Effectiveness (CATME) online peer evaluation instrument was very effective in reducing social loafing and allowing students to have a voice in communicating any teamwork challenges.

A team size of 4–5 should be chosen for design projects 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 [53]. Of the three possible group formation methods (self-selected, instructor-selected or random), instructor-selected is generally regarded as the most effective method [53, 54]. Before teams are formed, students can complete a questionnaire distributed based on criteria as selected by the course director. These criteria could include GPA, gender, personality, learning style and previous experience. By using these criteria to form diverse teams, our students have reported that they significantly improved their teamwork and communication skills. The online tool Team-Maker [54] can be used to conduct the student questionnaire, and form the teams.

6. Conclusions

In this paper, a review of the pressures that current engineering practice and education are under was conducted. The skills of graduates in Engineering have changed from practice oriented to knowledge oriented following the second world war. Recently, there has been a shift and the graduate outcomes of Teamwork, Communication, Data Analysis and Problem-Solving were identified as specifically important to emphasize in modern engineering education. Engineering design project courses, both capstone and cornerstone are most closely linked to engineering practice and can be used to emphasize these graduate outcomes, as well as most of the other required graduate outcomes. Engineering design competitions were identified as ideal sources of projects for these design project courses and some tools and strategies for creating an environment that supports teamwork and communication. It was shown that the teaching styles of Project Based Learning and Cooperative Learning are both ideally suited to be used with these types of projects.

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