Teaching and learning design engineering: 
What we can learn from co-curricular activities

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Abstract
A gap exists in the effective teaching and learning of design engineering. The Design graduate attribute is one of 12 attributes developed by the Canadian Engineering Accreditation Board to which Canadian universities must comply across engineering curriculum. This paper discusses how student run design-build-test-compete co-curricular activities meet CEAB Design graduate attribute indicators using the example of the SAE International Collegiate Design Series (CDS) team at Concordia University, Concordia SAE. Advantages, challenges, and recommendations are made for integrating aspects of the co-curricular platform into existing academic infrastructure in the interest of attributing accreditation units to this type of design experience. This approach would improve accessibility by providing all students the opportunity to participate in co-curricular-like activities, improve resource allocation to co-curricular activities, and improve student engagement and motivation in engineering design learning.

1. Introduction
Concordia University defines Experiential Learning as learning by doing, by which optimal learning outcomes are achieved through “experiential learning, followed by reflection, abstraction, experimentation, and looping back to concrete experiential learning.” [1]. Within the context of teaching and learning, a domain often associated with experiential learning is that of engineering design. While several methodologies for learning design, such as project-based learning [2] [3] and experiential learning [4] [5], are currently employed in classrooms, research and funding initiatives calling for the improvement of design engineering education indicates that gaps still exist in the methods employed for the effective teaching and learning of design engineering [6] [7] [8] [9].

One resource not yet explored for design engineering learning within the Canadian context is that of student involvement in design-build-test-compete co-curricular activities. Several studies have examined the effects of co-curricular involvement on learning effectiveness, leadership, employability, academic success, and ethical development [10]-[15], yet a gap exists in the research as to how universities can integrate some of the co-curricular approaches within the curriculum in such a way as to meet the CEAB Engineering Design Graduate Attribute requirements. The integration of co-curricular activities with credited coursework would facilitate student participation in engineering design competitions while at the same time allowing engineering faculties to increase the accredited design content of their curriculum. Some examples of design-build-test-compete projects are the Great Northern Concrete Toboggan Race [16], Spaceport America Cup [17], Canadian Satellite Design Challenge [18], and AIAA Design Build Fly [19], all sharing similar product lifecycle phases, and resulting in a prototype demonstration and design review competition.

This paper seeks to answer the question “How can we facilitate student participation in engineering design competition teams, encourage the participation of faculty mentors, and, at the same time, increasing student motivation and success in engineering science courses?”. The discussion uses the SAE International's Collegiate Design Series (CDS) [20] design-build-test-compete projects team at Concordia University [21] as an example. The suitability of the CDS activities for developing the graduate attributes in general, and the Design graduate attribute in particular, are assessed by comparison with curricular activities that are currently accepted for consideration when evaluating program suitability for CEAB accreditation units (AUs). Methods for better integrating aspects of the co-curricular platform into the engineering classroom curriculum are proposed, in the context of improving the accessibility of this type of experiential learning while also enhancing the engineering design education curriculum.

1.1 About Concordia SAE
Concordia SAE is a student-run chapter of the SAE International Collegiate Design Series (CDS) housed at the downtown campus of Concordia University in Montreal, Québec. The main objective of the society is to maintain a safe and supportive environment in which students can design and build SAE International vehicles, with the intention of competing them in SAE International Collegiate Design Series competitions.” [22]. The prototype vehicle categories and associated regulations and standards are set by SAE International. Concordia SAE is comprised of about 100
Design activities take place in a dedicated design space on the Concordia campus in downtown Montreal. The space allows students a common area in which to use design tools, assemble and disassemble physical components, and collaborate freely between and after classes.

The primary design objectives of each CDS competition undertaken by Concordia SAE are summarized in Table 1. The SAE International Collegiate Design series was chosen as the case study for this investigation because of the clearly defined design objectives associated with each of the competition classes.

Table 1: SAE International Collegiate Design Series objectives

| Competition                  | Objectives                                                                                                                                 |
|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| SAE Aero Design              | “The Regular Class is an all-electric class intended to develop a fundamental understanding of aircraft design.” [23]                       |
|                              | “The Advanced Class is an all-electric class designed to inspire future engineers to take a systems approach to problem solving, at the same time, exposing them to explore the possibilities of autonomous flights.” [23] |
| Baja SAE                     | “Each Baja SAE team’s goal is to design and build a single-seat, all-terrain, sporting vehicle whose driver is contained within the structure of the vehicle.” [24] |
| Formula SAE (Combustion and  | “The Formula SAE® competitions challenge teams of university undergraduate and graduate students to conceive, design, fabricate, develop and compete with small, formula style vehicles.” [25] |
| Electric)                    | SAE Supernaleage                                                                                                                             |
|                              | “The engineering design goal for SAE Supernaleage is to develop a single person, extremely high fuel economy vehicle that complies with the Supernaleage rules.” [26] |

1.2 CEAB accreditation criteria
The Canadian Engineering Accreditation Board (CEAB) assesses Canadian engineering programs based on 5 accreditation criteria: Graduate Attributes, Continual Improvement, Students, Curriculum Content and Quality, and Program Environment [27]. The study that is the subject of this paper considers the Graduate Attributes and Curriculum Content and Quality criteria. The Graduate Attributes criterion considers 12 graduate attributes, but only the Engineering Design Graduate Attribute is considered in detail as part of this study.

1.2.1 Design graduate attribute criterion
The CEAB describes the Design graduate attribute as “An ability to design solutions for complex, open-ended engineering problems and to design systems, components or processes that meet specified needs with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations.” [27]

The CEAB assesses the suitability of the program with respect to the graduate attributes based on five criteria: Organization and engagement, Curriculum maps, Attribute indicators, Assessment tools, and Assessment results [27]. The study that is the subject of this paper primarily considers the Indicators criterion.

1.2.2 Curriculum content and quality criterion
The curriculum content and quality are assessed using an approach based on the accreditation unit (AU). AU's are defined and assigned based on “contact time between the student and the faculty members, or designated alternates, responsible for delivering the program.”. This definition is most often used to evaluate AUs associated with lectures, tutorials or laboratories. However, CEAB recognizes the quality of other types of curriculum including “design or research projects, problem-based learning or other similar work officially recognized by the institution as a degree requirement” with an equivalent measure of accreditation units. The CEAB recognizes courses and learning experiences that do not follow the traditional lecture/lab format and suggest the use of a “K-Factor” for institutions that wish to claim AUs for such non-traditional curriculum content. Examples provided by the CEAB with respect to the Design graduate attribute include AUs for final year group design projects, where students work in teams and have very few contact hours with faculty; co-op or internship programs for which institutions award university credits; field camps; and problem-based learning projects that have associated university credits [27].
2. SAE Collegiate Design Series and CEAB accreditation criteria

In this section, a typical set of attribute indicators for the Design graduate attribute have been taken from [28] and are used to present the suitability of the SAE CDS activities for AU consideration. In Section 3, the advantages and disadvantages of the co-curricular design-build-test-competitions projects are discussed and compared to conventional lecture/lab courses, co-op and internship terms, and final year culminating activities (capstone projects). Some barriers to the implementation are presented and solutions proposed.

Table 2: Design attribute indicators

| Indicators                                      | Indicator description                                                                 | Concordia SAE                                                                 |
|------------------------------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| DE.1 - Understands the problem and defines objectives and constraints | • Understands the nature of the complex/open-ended engineering problems             | • Complex open-ended engineering problem is a premise of CDS competitions     |
|                                                | • Defines the functions and objectives                                                | • Read and apply competition rules and regulations                            |
|                                                | • Identifies technical constraints as well as constraints set by factors such as health, safety, engineering standards, etc. | • Design cycle includes analyzing the problem through constraint identification |
| DE.2 - Develops a design process considering health and safety risks, applicable standards, economic, environmental, cultural and societal considerations | • Develops a process to design systems, components and/or processes to solve complex and/or open-ended engineering problems | • SAE Concordia standardized design process, adapted to individual vehicular requirements |
|                                                | • Breaks down the complex problem into sub-problems                                 | • Original problem complexity broken down by sub-system and engineering discipline. Breakdown reflected in organizational structure and leadership protocols. |
|                                                | • Is capable of conceiving and inventing a plan considering health and safety risks   | • Health and safety certification is required, WHIMS training, continuous engagement with Concordia University Environmental Health and Safety (EHS) [29] department, documented safety procedures for prototype testing |
|                                                | • Is capable of conceiving and inventing a plan considering engineering standards and codes | • SAE required documented conformance to design standards, design and process Failure Mode and Effects analysis required for all projects. |
|                                                | • Is capable of conceiving and inventing a plan considering economic, environmental, cultural and societal issues in design | • Team project budget management and fundraising. Assuring inclusiveness in the team. Recycling and waste management for prototype build and test. |
| DE.3 - Researches and develops possible solutions to a complex engineering problem and recommends a final design | • Conceives alternative design solutions that meet most of the desired functions and objectives | • Initial CAD designs, hand calculations and mock-ups leading to design iteration and final configurations selection |
|                                                | • Systematically identifies and justifies an appropriate design that satisfies all requirements (functions, objectives, and constraints) and considers implementation issues. | • Systematic team design reviews in consultation with faculty supervisors, laboratory technicians and engineer-in-residence |
|                                                | • Performs Design calculations                                                        | • Prior to modeling and simulation, students assess design decisions through hand calculations and software computing tools. |
| DE.4 - Implements and evaluates a final design  | • Validates the design against the problem specifications                             | • Modeling and simulation, subcomponent prototype build and test              |
|                                                | • Transforms conceptual design to a detailed design                                  | • Final drawing and report preparation, validation against requirements, team buy-off leading to vehicle build and test. Vehicle evaluation at competition, expert evaluation of design report by engineering judges |
|                                                | • Integrates engineering, computer, and mathematical principles to resolve all the constraints involved in the design process to take into account economic, health, safety, social and environmental factors, engineering codes of practice and applicable laws | • Use of engineering core curriculum courses to evaluate design and team practice for conformity to laws and regulations, health and safety standards and ethical considerations. Sustainable practices for re-use and recycle of materials and subcomponents. Waste management. |

The list of activities in Table 2, and their association with the Design graduate attribute indicators makes a convincing case for the suitability of the SAE project for engineering design attribute accreditation. The strength of the SAE activities with respect to the Design attribute are in the breakdown of the problem, the design of sub-systems and components, the mandatory consideration of regulatory constraints, and the implementation and evaluation of the final design.

2.1. DE.1 - Understands the problem and defines objectives and constraints

The SAE competition student team is provided with a document defining the competition objectives as well as the regulations constraining the vehicle design, performance and competition rules. The stated intent of each CDS competition is to "provide undergraduate and graduate engineering students with a real-world design challenge” [23]. The hosting
competition in which the team is registered provides the students with a set of objectives and safety-driven requirements. A Design Rules document is developed by a rules committee for each competition team, and made available online through the SAE International website [30] [31] [32] [33].

The objectives, rules, and guidelines for the competition are intended to reflect real-life product development scenarios, constrained by customer requirements, regulation, cost, and safety requirements. The use of these requirements documents provides the students with an opportunity to decompose, understand, and track their own compliance throughout the product lifecycle.

The rules documents cover topics from competition entrance eligibility such as student status and SAE membership; to design requirements such as the minimum visibility requirements specification for SAE Supermileage shown in Figure 2; and competition events such as the static and dynamic events in Baja and Formula SAE [24] [25].

![Figure 2: SAE Supermileage minimum visibility plane specifications](image)

### Table 3: Competition team technical sub-disciplines

| AeroDesign | Baja | Formula Combustion | Formula Electric | Supermileage |
|-----------|------|-------------------|----------------|-------------|
| Aerodynamics | Brakes | Aerodynamics | Accumulator | Body |
| Propulsion and Electrical | Electrical | Brakes | Aerodynamics | Electrical |
| Structures | Drivertrain | Chassis | Brakes | Powertrain |
| Manufacturing | Frame | Data Acquisition | Chassis | Steering |
| 3-D Modeling | Finish and Assembly | Drivertrain | Cooling |
| Initial Seating | Steering | Electrical | Drivertrain |
| Final Assembly | Suspension | Engine | Steering |
| | Wheels and Tires | Ergonomics | Suspension |
| Manufacturing | Fit & Finish | Wheels and Tires |
| | | Manufacturing |
| | | Steering |
| | | Suspension |
| | | Wheels and Tires |

2.2 DE.2 - Develops a design process considering health and safety risks, applicable standards, economic, environmental, cultural and societal considerations

The Concordia SAE is comprised of five competition teams, and each team proceeds through the prototype design cycle shown in Figure 3.

![Figure 3: Concordia SAE design cycle](image)

To deal with the complexity of the multidisciplinary design process, each team is organized in various sub-disciplines, in accordance to their respective vehicle. Typical technical sub-disciplines associated with each team division are listed in Table 3.

Teams typically have between 10 – 25 active members, and are led by a Team Coordinator who works with Subteam Captains to develop a plan that will take the project through the process in Figure 2 from the receipt of the rules and regulations to the final competition and reporting stage within the timeframe associated with the competition. Subteam members are responsible for tasks contributing to design, analysis, build, verification, testing, validation, reporting and presentation of a subsystem. The experience echelon functions on a principle of mentorship, where more experienced SAE members train new members to maintain design continuity through transference of information, and prepare the next generation of team leads, team coordinators, and society executives.

Safety is one of the most important aspects of merging prototype development with engineering training. Student-built prototypes have inherent risk, and require robust risk management to ensure appropriate mitigation strategies are implemented to operate safely. Concordia University works in close conjunction with Concordia SAE to develop and enforce safety procedures, safety training, and a culture of individual responsibility for safe practices. An example of this can be found in the testing procedures document developed by the Engineering Design and Manufacturing Laboratory (EDML) team [34], shown in Figure 4. Learning to create testing procedures ensuring safe practice reflects the safety protocol rigor seen in industry.

In addition to regulations, students must consult several standards referenced throughout the rules documentation. For example, all competing teams must consult the SAE J1739 – Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) [35].
A university project must be centered around sustainability to ensure future students are given the opportunity to participate. Most resources, especially financial, are hard-earned by the students, and must be carefully managed.

- Ethical economic management of a $150,000 budget and financial transparency is mandatory. Concordia SAE is under the umbrella of an accredited managing student society that receives annual financial audits.
- Social professionalism amongst team members and outside of the society reflects both the integrity of Concordia SAE and of Concordia University.
- Health and safety certification, documentation, and procedure are enforced for safe operation and environmental responsibility. This is accomplished through Workplace Hazardous Materials Information System (WHMIS) training [36], continuous engagement with Concordia University Environmental Health and Safety (EHS) [29] department.
- Legal integrity requires communication with the Montreal community to secure testing permission and insurance coverage, and appropriate certifications such as driver’s or flying licenses for vehicle operation. Traveling for competition requires the appropriate documentation to enter the United States with prototype vehicles.
- Concordia SAE students apply environmental sustainability concepts by re-using materials and conserving scrap materials for future projects, and using upcycled workspace furniture.

2.3 DE.3 - Researches and develops possible solutions to a complex engineering problem and recommends a final design

The Concordia SAE design process shown in Figure 3 includes an iterative design process where initial design concepts are developed using sketches, 3-D models, hand calculations and mock-ups. An incorrect, rushed or incomplete problem analysis and investigation often results in a very small design space, often referred to as “designing into a corner”. This problem is widely acknowledged in engineering design, where schedule and budget restraints often lead to an incomplete problem analysis and a correspondingly shrinking of the solution space. Students participating in the SAE competitions have the opportunity to experience this phenomenon first hand, and to see how previous years’ teams, as well as teams from other schools have responded to this difficult challenge. A major feedback mechanism to indicate success in problem solving is a physically working product, with substantiated decision and validated design choices both in a written report and in a presentation before a panel of industry experts at competition. While many designs result in working and well-understood vehicles, important engineering lessons in problem analysis and investigation are learned when systems fail, as illustrated in Figure 5, and students are given the opportunity to learn from their mistakes. This opportunity for failure and incremental engineering through design evolution is often absent from the classroom setting.

![AeroDesign wing failure and Formula Combustion hub failure](image)

Simulation and test-benches are used to prototype and test individual components and sub-systems. The systems are integrated and procedures implemented to verify that the assembled vehicle meets competition regulations, that the appropriate documentation is in place and signing authorities identified. The risk analyses and safety precautions are documented, and vehicle performance is validated through sensor installation, data collection and analysis.

**2.4 DE.4 – Implements and validates a final design**

For any CDS competition, at the outset of the design cycle students are required to spend time analyzing the problem, identifying its constraints, and developing a solution within that design space. Problem analysis for CDS teams will often start from an existing design, where students must first understand the current design, identify areas of design improvement opportunity through analysis and validation, and create a functional and improved design that is again substantiated by testing and validation. Students learn that an effective and considered use of mathematics, engineering sciences and computer simulation allows them to better understand the limitations and optimize the performance of their product prior to building their prototype vehicle.

Investigative methods at Concordia SAE include past vehicle data benchmarking, hand calculations, 3-D modeling, simulation such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD), test bench experiments using equipment such as engine and chassis dynamometers, wind tunnel testing as shown in Figure 6, and track and flight testing. Data acquisition systems are installed and calibrated prior to testing, and collected data is cleaned up, analyzed, and
summarized in representations such as graphs and charts for reporting, presenting, and iterative purposes.

A typical CDS competition requires students to develop a functional vehicle or vehicle system. Each vehicle design is based on the application of fundamental engineering sciences in subjects such as aerodynamics, vehicle kinematics, manufacturing processes, electrical harness design, radio control system, and remote data acquisition capabilities. Examples of applied engineering knowledge base through AeroDesign aircraft takeoff distance calculations and Supermileage composite manufacturing processes are shown in Figure 7. Prototyping and testing require students to validate their assumptions, and question their understanding when test results do not necessarily agree with predicted performance based on analytical approaches.

Students in Concordia SAE learn to use a wide variety of hardware and software tools to design, analyze, build, and test their vehicles including:

- Software tools such as SolidWorks, as shown in Figure 8, and CATIA for CAD and FEA/FEM, ANSYS for CFD, CarSim, MatLab, Microsoft Suites;
- Manufacturing tools and processes such as laser and waterjet cutters, lathes, mills, drill presses, a CNC, welders, rivet guns, and composite molds and layup;
- Testing and data collection tools including engine dynamometers, thrust test bench, chassis dynamometer, chassis torsion rig, microcontrollers, and strain gages.

All teams are required to submit a written design report and must partake in at least one presentation component during competition. Students must present and defend their design decisions to a panel of industry experts. All teams are required to demonstrate an effective response to clear instructions by passing a technical inspection prior to operating their vehicle at competition. Vehicle regulatory compliance must be verified and approved by competition officials. Students also gain experience communicating technical content with different audiences, including sponsors and the greater Montreal community by synthesising information into different forms of technical and non-technical communication such as reports, emails, and phone-calls.

3. Discussion

This paper argues that students participating in design-build-test-compete co-curricular activities such as the SAE CDS competition teams are engaging in project-based experiential learning that meets all the CEAB Design attribute indicators.

3.1 Advantages of CDS learning model

There are other advantages associated with the student team experience. Students are motivated by the excitement of the competition, they feel valued by their team-mates, and benefit from concrete feedback in the form of the results of their contributions [39]. The comradery, autonomy, accountability, and purpose-driven learning experienced by students in this setting can be attributed to a platform where deliverables have meaningful consequences on the current team’s success, and can impact both the learning experience and success of future teams. In a final year Capstone project, smaller teams, discontinuous projects, uni-disciplinarity, and grade-driven deliverables can have a negative impact on individual and team motivation. While the quality of a co-op or internship experience can vary significantly, it can be challenging to establish a meaningful and rewarding project through which a student will feel valued for their contribution to the company. While a co-op or internship will involve more direct supervision, students are given little if any decision-making
control, and are likely limited in their involvement with design and engineering.

3.2 Disadvantages of CDS learning model
Design-build-test-compete co-curricular activities such as the Concordia SAE CDS have shortcomings. Co-curricular involvement typically requires a significant time commitment to obtain value-added engineering experience, and is therefore often not accessible to non-traditional students with responsibilities such as jobs or families. Conversely, students who are the most dedicated to co-curricular projects almost invariably do so at the expense of their GPA. This further reduces the accessibility to students under stringent GPA constraints, such as the case for conditions applied to maintaining scholarships, student visas, and admission to other academic programs. Additionally, as most co-curricular activities are not recognized by their host universities for academic credit, faculty and staff receive no recognition or incentive toward supervisory involvement. Co-curricular projects therefore either depend heavily on altruistic university employees, or make do with a minimum of supervision, professional consultation and mentorship.

3.3 Barriers to implementation
One of the most significant barriers to better leveraging co-curricular advantages and mitigating the disadvantages is the university recognition of co-curricular activities for academic credit. While the equivalent AU K-Factor evaluation mechanism for non-traditional lecture/lab courses could be applicable in this instance, CEAB will not attribute AUs to "work that is not officially recognized by the institution as a degree requirement" [27]. Implementing methods of evaluation while maintaining an autonomous student-run environment would be challenging, and would require additional resources from the university to implement and sustain an evaluation structure on the existing platform. At Concordia University, students in co-curricular activities are primarily supervised, supported, and instructed by the Engineers in Residence and technician staff, both within and outside working hours. While the university supports this contribution, further resource allocation is limited by a lack of academic acknowledgement.

If it is possible to convince the institutions to recognize design-build-test-compete co-curricular activities such as the SAE CDS learning activities with academic credits towards their degree requirements, it would unlock solutions that could overcome many of the disadvantages discussed in the previous section. This would allow a greater number of students access to this unique model of experiential learning, while at the same time promoting more interest and participation from faculty and staff, and increasing the number of design AUs for the institutions.

3.4 Proposed solutions
To overcome these barriers, two solutions are proposed to integrate co-curricular aspects into existing university accreditation unit infrastructure: through capstone projects and engineering science course projects.

A final year Capstone project is already implemented at many Canadian institutions across engineering undergraduate programs. Traditional Capstone projects at Concordia University consist of small 4-5 student teams, span over two semesters, and typically require the design, build, test, and validation of a working prototype or service. Concordia incorporates two approaches to co-curricular project models in Capstone: one in which a capstone team has no prior co-curricular experience or involvement, and one in which most of the capstone team members have been actively involved in a co-curricular for more than a year. In the former, co-curricular teams collaborate with Capstone faculty and staff to propose non-critical path research and development project opportunities. The capstone teams that undertake these projects receive some of the benefits of co-curricular infrastructure, and the co-curricular projects benefit from the project findings and can choose to incorporate design solutions into future prototypes. This model could be further developed to incorporate several Capstone teams working on different subsystems of a CDS-like prototype, adding teamwork, communication, and system integration dimensions to the learning experience, and systematically increasing the number of co-curricular capstone project opportunities.

Aspects of these platforms could also be integrated into single-semester engineering science course projects. Many applications of the engineering sciences can be found in co-curricular projects, and a similar R&D proposal approach to that of Capstone could be taken into a course project setting. Challenges of this proposal would involve managing resources to plan, track, and re-integrate a larger number of projects; dealing with the fluctuating nature of co-curricular activities due to student turnover; and sufficient in-course design supervision and project expertise. Advantages include increased accessibility to the co-curricular experience, the leveraging of existing platforms for coursework, and an increase in Design attribute AUs across the curriculum. The implementation of this type of opportunity may require a course-project manager or integrator position, but could result in an improvement in course content interconnection over the curriculum, thereby improving student’s perceived relevance of course content, and further improving motivation and engagement.

4. Conclusion
While there are many advantages to the design-build-test-compete co-curricular activities as demonstrated by the example of Concordia SAE Collegiate Design Series, the
aspects that contribute most to an enriching learning experience are:

- Hands-on design experience
- Opportunity for failure and iteration
- Peer mentorship
- Meaningful work

A primary motivation for integrating aspects of the co-curricular model into academic contexts such as capstone and engineering science course projects is to improve resource allocation, promote equity by increasing accessibility to this type of university experience thereby improving student motivation and success, recognize the value gained through engineering design experiential learning, and contribute to improving the quality of engineers graduating from accredited Canadian university engineering programs.

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