Best practices review of first-year engineering design education

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Abstract

This work reviews best practices in first-year engineering design courses at 40 universities across Canada and the United States. The authors reviewed the subject matter and instructional methods of these engineering design courses. University selection was based on prominence, level of engineering design content, and availability of data. The authors narrowed the scope of the study to seven Canadian programs and eight American programs for further investigation: University of British Columbia, University of Calgary, University of Manitoba, Queen's University, University of Sherbrooke, University of Toronto, University of Western Ontario, University of Colorado, Franklin W. Olin Engineering College, Harvey Mudd College, Massachusetts Institute of Technology, Northwestern University, Rensselaer Polytechnic Institute, Stanford University, and Virginia Polytechnic Institute. The authors then identified six reoccurring themes in the methods of engineering design instruction: full-scale project, small-scale project, case study analysis, reverse engineering project, design tools and methods instruction, and integration. These themes are then discussed from the point of view of educators looking to develop first-year engineering design courses.

1. Introduction

This work summarizes the best practices in first-year engineering design education programs at universities across Canada and the United States. It aims to offer background information for educators looking to implement or enhance design courses in their first-year programs.

The authors found evidence of over a decade of growth in first-year design courses in engineering programs; however the evidence was primarily anecdotal and indirect. Anecdotal evidence was gathered during informal discussions with current engineering educators. The indirect evidence was shown by the number of conference and journal publications on the topic of new first-year design courses. Though this circumstantial evidence was extensive, direct evidence was infrequent. Only one extensive review of design in the first-year was found for American programs [1] and none was found for Canadian programs.

This work is an effort to uncover direct evidence of engineering design courses in first-year programs, identify the best instructional practices used, and present this information in a format useful for educators looking to implement or enhance first-year engineering design courses.

2. Methodology

This study is broken down into two stages: a preliminary study, with the intent of identifying first-year engineering design courses; and an expanded study, with the intent to delve deeper into select courses in order to identify best practices.

2.1 Preliminary study

The intent of the preliminary study was to collect quantitative data on the current prominence of engineering design courses in Canadian first-year programs without a major expenditure of resources. The authors selected 12 Canadian engineering programs based on anecdotal and indirect evidence of first-year engineering design courses. They reviewed online sources of these courses and programs, principally academic publications, websites, and

university calendars. Each course within the programs studied was evaluated by the authors on whether it had sufficient engineering design focus to be classified as an engineering design course. The academic unit value of all courses, both engineering design courses and non-engineering design courses, was noted.

2.2 Expanded study

After the preliminary study confirmed the presence of engineering design courses in first-year programs, the authors expanded the study in both depth and scope. The expanded study included 40 Canadian and American engineering programs. The programs studied were primarily first-year; however some upper-year courses were included as noteworthy examples. The authors selected the universities based on anecdotal and indirect evidence as well as the results of the preliminary study. As with the preliminary study principally online sources were used; however additional investigation was

conducted through phone interviews with course founders, instructors, and coordinators. The authors also visited the University of Calgary and the University of Manitoba to conduct in-person interviews with course coordinators, instructors, teaching assistants, and current students, and to better understand the facilities and environment. A summary was created for 18 of the 40 programs studied in the expanded study.

3. Results and discussion

The results from the preliminary study were used to guide the data collection for the expanded study.

3.1 Preliminary study

The quantitative data collected is summarized in Table 1 and includes: identification of engineering design courses; the sum of all engineering design course academic unit value; and the sum of the academic unit value of the first-year program. The ratio of engineering design course academic units to

Table 1. Percentage of design by academic unit in the first year at selected Canadian universities

University name	First-year design course name(s)	Engineering design course academic units	Program academic units	Engineering design in first-year (%)
University of Western Ontario	Engineering design and innovation studio	2	7.5	26.7
Queen's University	Practical engineering design modules Professional engineering skills	114	558	20.4
University of Toronto ¹	Engineering strategies and practices I and II	1	5 – 5.5	18 – 20
Ecole Polytechnique ¹	Various	1 – 5	33 – 27	3 – 18.5
University of Calgary	Engineering design and communication I and II	1	5.5	18.2
University of British Columbia (Okanagan)	Engineering fundamentals	6	36	16.7
University of British Columbia (Vancouver)	Engineering case studies	6	36	16.7
University of Waterloo (Systems Design)	Introduction to system design	0.75	5.25	14.3
University of Guelph	Engineering and design I	0.75	5.25	14.3
Dalhousie University	Engineering design and graphics	3	27	11.1
University of Saskatchewan	Engineering 2	3	33	9.1
University of Manitoba	Design in engineering	1	36	8.3

1 - The program is specialized in the first year, with slightly different schedules for each specialization. The percentage range covers all these specializations, except for Engineering Science at the University of Toronto.

total program academic units is calculated and tabulated in the fifth column of Table 1 to allow comparison across programs.

The percentages of engineering design courses in first-year programs range from 8% to 26% (see Table 1). This was sufficient indication for the authors to justify an expansion of the study to include additional universities and to delve deeper into the engineering design course content in order to determine best implementation practices.

It is recognized that the actual engineering design content in each of the courses identified in Table 1 varies widely. Therefore this metric is merely a rough indicator of the level of prominence that engineering design holds within the first-year programs at various Canadian universities, and is **not** tied to the design content as ranked by the Canadian Engineering Accreditation Board.

3.2 Expanded study

The analysis of the 40 programs led to the identification of six common instructional methods for engineering design: full-scale project; small-scale project; case study analysis; reverse engineering project; design tools and methods instruction; and integration. These are **not** different types of design

courses, but rather the various methodologies used within those courses. This distinction is important, because most design programs contain multiple instructional methods.

For 15 of the 40 programs there was sufficient information to identify the instructional methods used in their first-year engineering design program. Table 2 summarizes these methods for seven Canadian programs, and Table 3 summarizes the methods for eight American programs.

Of interest in Table 2 is that all Canadian programs use a minimum of two methods, with some using as many as four. Design tools and methods instruction and small-scale projects are the most popular methods, being used in six of the seven Canadian programs. Full-scale projects follow close behind, being used in five of the seven programs. Reverse engineering projects and integration appear infrequently, used only in one of the seven programs.

As shown below in Table 3 the eight American programs use two to four instructional methods each. Design tools and methods instruction and small-scale projects are common, used in seven of the eight American programs. Of those eight programs none use integration, while reverse engineering projects are being used in three.

Table 2. Engineering design instructional methods for selected Canadian first-year programs

	Full-scale Project	Small-scale Project	Case Study Analysis	Reverse Engineering Project	Design Tools and Methods Instruction	Integration
University of British Columbia			√		√	
University of Calgary	√	√			√	
University of Manitoba		√			√	
Queen's University	√	√	√		√	
University of Sherbrooke	√	√		√		√
University of Toronto	√	√	√		√	
University of Western Ontario	√	√			√	

Table 3. Engineering design instructional methods for selected first-year American programs

	Full-scale Project	Small-scale Project	Case Study Analysis	Reverse Engineering Project	Design Tools and Methods Instruction	Integration
University of Colorado	√	√	√		√	
Franklin W. Olin Engineering College		√			√	
Harvey Mudd College	√	√		√	√	
Massachusetts Institute of Technology		√	√	√	√	
Northwestern University	√				√	
Rensselaer Polytechnic Institute		√		√	√	
Stanford University		√			√	
Virginia Polytechnic Institute		√	√			

3.2.1 Full-scale project

A full-scale project is a major engineering design project that spans at least six weeks and sometimes as much as one or two full terms. Students generally work in teams of 2 to 10, and so the method is better suited to a design studio environment than to a lecture hall. The project duration is sufficient that teams can undertake a broad portion of the design process, in many cases implementing their designs. A mentor or facilitator is normally assigned to each team, usually a faculty member, teaching assistant, or industry representative, to act as an ongoing resource. Industry, faculty, students, community organizations or competitions can be the source of projects. All student teams may work on the same project, or each team may have its own project. Deliverables vary but often include a detailed engineering design or a prototype or proof of concept.

Institutions using full-scale projects include University of British Columbia (Okanagan), University of Calgary, Queen's University, University of Sherbrooke, University of Toronto, University of Western Ontario, Boston University,

University of Colorado, Elizabethtown College, Harvey Mudd College, Northwestern University, and Trinity College (Hartford).

The greatest strength of full-scale projects are that they allow sufficient time for students to experience a large portion of the design process. On the other hand, full-scale projects typically limit exposure to a single project over the course of a term. A single project keeps students from experiencing different types of projects, and means they do not experience multiple successes and failures. The full-scale projects also tend to be the most resource-intensive method.

Noteworthy examples

APSC112: Engineering Strategies and Practices II, at the University of Toronto: Students work in teams of five on a major 13-week engineering design project. The projects originate externally, coming from engineering firms, non-engineering industry, community organizations, and the occasional individual. Recruitment of these projects is a major undertaking and is the primary

duty of one course instructor. Since the university values service-based learning, it is looking to increase the number of community-based projects. Past projects have included redesigning the logistics of a large company's mailroom, devising a method for a wheelchair-bound student to use a backpack, and developing a device to measure lateral movement on a snowmobile. All teams take the project from needs analysis to detailed engineering design, with exceptional designs moving into implementation with a budget of CAD\$200 [S. McCahan, personal communication, November 9, 2006; 2].

APSC100: Practical Engineering Design Modules, at Queen's University: First-year student teams work on a 10-week project. Each project is unique, and approximately 25% result in either a proof of concept or a prototype. Faculty members and community groups are the primary source of project ideas. Past projects include the design and construction of a rudimentary fiber-optic communication system, an educational apparatus for demonstrating a scientific principle to K-12 students, an assistive auto-entry device for a disabled client, and a hydraulically controlled robotic arm [D. Strong and B. Frank, personal communication, November 3, 2006, November 13, 2006; 3-4].

3.2.2 Small-scale project

Small-scale projects range from a single classroom session to six weeks in duration. It is difficult to cover the entire design process within these shorter durations; therefore students usually concentrate on a subset of design process activities. This shorter duration allows time for students to undertake several projects over the course of a single term.

Small-scale projects are typically run with teams of 2 to 10 students, rather than individuals and, therefore, are better suited for a design studio environment than for a lecture hall. The same engineering design challenge is usually assigned to all teams, enabling evaluation through performance comparisons with other teams.

The final deliverable for a small-scale project is usually a final conceptual design or a proof of concept model, often with a performance-measuring competition, an oral presentation, or a brief report.

Institutions using small-scale projects include University of Calgary, University of Manitoba, University of Sherbrooke, University of Western

Ontario, University of Colorado, Franklin W. Olin Engineering College, Harvey Mudd College, Iowa State University, Massachusetts Institute of Technology, University of Nevada-Reno, Rensselaer Polytechnic Institute, Stanford University, US Coast Guard Academy, and Virginia Polytechnic Institute.

The limited time of small-scale projects has both positive and negative aspects. The shorter time frame allows more time to try a range of projects such as experiencing the different disciplines. This short time frame, however, generally precludes undertaking projects for clients outside the university. As a result, students may not experience those aspects of the design process that require client interactions. The resource demands for a small-scale project are typically much less than for a full-scale project. However, where this method is used, students typically undertake several projects in a series. As a result, the savings may only be slight relative to a single full-scale project. Finally, these projects are typically less technical in nature and can be more appealing to the general public. This makes them better suited for use at public events for the promotion of the engineering profession.

Noteworthy examples

ENG1430: Design in Engineering, at the University of Manitoba: This single-term course contains four small-scale engineering design projects, each introducing students to a different discipline. The students are required to design and build each of the following projects: a tower out of simple materials (Civil); an elastic-band-powered model car (Mechanical); a digital logic circuit control system for a model three-story elevator (Electrical); and a process to safely transport an egg over a given obstacle (Biosystems). This course has generated student excitement and ranks as many students' favourite first-year course [R. Britton, personal communication, September 13, 2006; D. Petkau & J. Frye, personal communication, October 26-27, 2006; 5].

3.2.3 Case study analysis

In case study analysis, students learn engineering design by studying the work of other design engineers. The cases studied can range from high-profile projects, such as the design for the Confederation Bridge, to local concerns, such as the

redesign of a park. By seeing the process of design in real-world applications, students are better able to understand the value of what they are learning and how it is applicable to their future careers. One notable subset of case study analysis is failure analysis. By examining the results of what happens when design engineers fail, students gain a level of respect for the process.

Case studies are usually presented in a lecture setting, either by faculty or by engineers who worked on the original case. Often this presentation is used as the catalyst for discussion, especially when the case addresses a controversial topic. In some courses, particularly the team-based courses, students are assigned the role of one of the players within the case. They then present and defend that player's point of view to the other students through debate or discussion sessions.

Student deliverables in case studies are often similar to lecture-based courses, with students writing assignments, examinations, or reports, or making oral presentations. In some schools, students are challenged to find their own solutions after the case study analysis is completed. This may lead into a small-scale project.

Institutions using case study analysis include University of British Columbia, Queen's University, University of Toronto, University of Colorado, Massachusetts Institute of Technology, San Jose State University, and Virginia Polytechnic Institute.

Case study analysis is an excellent way to introduce students to the engineering profession. By studying the engineering design work of practicing engineers, students can learn what is expected of engineers in the workforce. This method is, therefore, an effective means of conveying key ideas about professionalism. Implementation cost is low for this method as it can be taught in a standard lecture format. However, to increase student participation and interest, multiple sessions with smaller numbers of students to encourage lively discussion are highly desirable. Case studies are not well suited to addressing promotion, recruitment, and diversity issues. The greatest weakness of this method is the absence of hands-on components and of execution of the design process.

Noteworthy examples

APSC150: Engineering Case Studies, at the University of British Columbia: This course is divided into four case studies, each taught by faculty members from different disciplines. The current case studies are biological reactors, sustainability in engineering design, advanced material for commercial aircraft structures, and environmental impacts at a mine site. The life span of each case study is four years, so one new case study is brought in every year [P. Lawrence & B. Dunwoody, personal communication, October 06, 2006; 6].

APSC190: Professional Engineering Skills, at Queen's University: One workshop during a uniquely structured week of workshops introduces the case of the famous Quebec Railway Bridge failure, the often credited source of Canadian engineers' iron rings. The engineering design project in the course also has a strong case study component, as students are required to take on the role of a player in the case and then make a presentation from that player's perspective. Players in these cases include individuals from government, industry, and citizen groups [D. Strong & B. Frank, personal communication, November 06, 2006; D. Strong, personal communication, November 13, 2006; 7-8].

3.2.4 Reverse engineering project

In reverse engineering projects, students disassemble an inexpensive or obsolete device paying particular attention to document the procedure. Students learn good design practice by observing examples of it through a hands-on approach. The duration of these projects varies depending on the complexity of the device and the required deliverables, but usually the projects do not exceed a few weeks.

This method is suited to either individual or team efforts; however, it does require a design studio environment rather than a lecture hall.

Deliverables may include detailed manufacturing and design documentation (e.g. part and assembly drawings, component lists, material rationale, and manufacturing processes); oral presentations; reassembly of the device and/or instructions for reassembly; potential improvement recommendations; and final reports. This method rarely uses examinations as deliverables.

Institutions conducting reverse engineering projects include University of Manitoba, University of Fairbanks Alaska, Harvey Mudd College, Massachusetts Institute of Technology, North Carolina State University, Northwestern University, Rensselaer Polytechnic Institute, Rutgers University, and Iowa State University.

Reverse engineering projects teach the hands-on aspects of engineering design with relatively moderate resource costs. Facility requirements for these projects include a room stocked with flat tables, inexpensive toolsets, and used devices for disassembly. In the case of the reverse engineering of software, a computer lab will suffice. As with small-scale projects, the short time frame allows for multiple projects to be conducted in a single-term course, giving potential for promotion of all disciplines. Reverse engineering projects can expose students to most aspects of the design process. The greatest weakness of this method lies in the removal of the initial creative stages of the design process.

Noteworthy examples

BIOE2580: Biosystems Engineering Design Trilogy I, at the University of Manitoba: Though not a first-year course, this is an excellent example of a reverse engineering module. Second-year biosystems engineering students work in teams of two to disassemble a working power tool and document the disassembly process. They then pass their parts and documentation to a second group, which must return the power tool to working condition. The reassembly team then grades the disassembly team on the quality of their documentation [D. Petkau, personal communication, October 27, 2006].

3.2.5 Design tools and methods instruction

In this approach, students receive instruction on design tools and methods in a standard lecture format. In every course using this method, other methods are also used; however, the timing of this combination varied. In some courses, the instruction is presented first, or in a just-in-time manner, and then students apply the tools and methods on other projects. In other courses, students first undertake a design project and then receive instruction on design tools and methods. In the latter case, inefficiencies and failures experienced during the project reinforce

the value of these tools and methods at the time of instruction.

Deliverables produced by the students in this lecture-based course vary greatly. As in non-design courses, students may write assignments or exams testing their knowledge of the material. If this method is combined with other project-based methods, students may be required to exhibit their knowledge of the tools by using them in their projects.

Institutions using design tools and methods instruction include nearly every program studied: University of British Columbia, University of Calgary, University of Manitoba, Queen's University, University of Toronto, University of Western Ontario, University of Colorado, Franklin W. Olin Engineering College, Harvey Mudd College, Massachusetts Institute of Technology, Northwestern University, Rensselaer Polytechnic Institute, and Stanford University.

Design tools and methods instruction is the most commonly used method of teaching engineering design across Canada and the United States. This method is typically lecture-based and therefore uses facilities that are readily available at any educational institution with relatively high student-to-instructor ratios. In addition, a wide range of material including many theoretical aspects of engineering design can be covered in a short time. However, students need the opportunity to apply the theory to ensure the lasting impact of the material covered with this method.

Noteworthy examples

APSC111: Engineering Strategies and Practices I at the University of Toronto: With an enrollment of 1,000 students, this course has found a balance between resource demands and the desire for more personal laboratory time through use of design tools and methods instruction. Students receive lectures on the basics of engineering design methodology, team process, and professional communication; and to add social context to the design process, they receive instruction on integration of social factors, human factors, environmental impact, and economics. The intent is to deliver the lecture content in a timely fashion that will allow students to immediately apply that knowledge to other aspects of the course. For example, the mid-term transition from tutorial to small-group

discussion seminars is timed to match with the switch from process instruction to social factors [S. McCahan, personal communication, November 9, 2006; 2].

ENGG251: Engineering Design and Communication I, at the University of Calgary: The instructional team for this course, like the Engineering Strategies and Practices team at the University of Toronto, is required to deal with a large student population, currently 750. They too have opted to use lecture-based instruction; however, they have taken the noteworthy approach of integrating the lectures into the laboratory. Initially, they attempted to simply conduct full-length lectures on the design process within the laboratory, but found that student comprehension of the material taught in this way was low. They have since adapted their approach by eliminating the full lectures and instead interspersing short mini-lectures between other aspects of the laboratory. For example, a mini-lecture on Familiarization is conducted while students are in the laboratory working on this particular aspect of their engineering design projects. An additional noteworthy aspect of the lecture delivery is that it is broadcast simultaneously to four laboratories through an elaborate multimedia broadcast system. This approach also allows for the recording of lectures for playback at latter sessions [D. Caswell, personal communication, September 11, 2006; D. Caswell, personal communication, October 23-25, 2006; 10-11].

3.2.6 Integration

In a traditional engineering program, individual courses are relatively independent of each other. Prerequisites control sequencing, but do not ensure real connections or dependencies.

In an integrated program, linkages are created among courses where, in traditional programs, none exist. These linkages can take many forms. In one form, courses are coordinated so that material from one course can be applied in another course in the same academic term. For instance, a subject introduced in a mathematics course (e.g., Fourier Series Analysis) this week can be used next week in an engineering science course (e.g., Signal Processing). In another form, assignments can be “shared” between courses. For example, a laboratory report can be submitted

first as an assignment in a technical communications course. Once it has met an acceptable standard, the report is then submitted for technical evaluation in the laboratory course.

In its most ambitious form, an integrated program comprises a suite of courses interwoven around and in support of a common project, possibly an engineering design project. These projects can be based in a separate projects course or can exist only at the intersection of the contributing courses. The projects are selected so that students can use the knowledge that they have learned in the contributing courses.

Institutions having fully or partially integrated programs include University of British Columbia, University of Calgary, University of Sherbrooke, University of Alabama, Arizona State University, Colorado School of Mines, Drexel University, Embry-Riddee Aeronauticae University, University of Hartford, Louisiana Tech University, University of Massachusetts Dartmouth, North Carolina State University, Ohio State University, Rose-Hulman Institute of Technology, and Texas A&M University.

Implementation of fully integrated methods of instruction represents a radical and exciting departure from traditional engineering programs, but requires an exceptional dedication of resources. Once in place, however, integration is an exceptionally effective method instructing engineering design. It is, however, possible to implement lower levels of integration at lower costs [12]. One of the key benefits of integration that can be retained at these reduced levels is the creation of linkages between courses focused on engineering science and courses focused on engineering design.

The benefits of an integrated program include: reinforcement and demonstration of relevance of fundamental concepts through application; development of a greater awareness of the engineering “big picture”; and a higher level of collaboration among teaching faculty. In an extensive study of integrated programs across the United States [13], integrated programs were found to increase student GPAs and retention of material; student confidence in problem-solving, studying, teamwork, time management, reading, writing, speaking, and computing skills; and retention of students, especially

in under-represented groups. The principal disadvantage of program integration is the commitment of faculty and staff time that is required to manage the organizational aspects.

Noteworthy examples

Mechanical Engineering Integration Projects, at the University of Sherbrooke: The courses within this program are integrated in three ways. First, each term is characterized by a common theme, for example, Newtonian dynamics in the first term of the first year. All content taught within this term is done from this frame of reference. For example, differentiation is taught using the concepts of rates of change, particularly velocity and acceleration.

The second form of integration is accomplished through just-in-time course linkages. For example, immediately after students have received instruction on differentiation in their calculus course, they begin using it to calculate velocity and acceleration in their dynamics course, thus giving the knowledge context and a readily apparent application.

The final form of integration is implemented through integration projects. These carefully selected first-year projects are all real-world problems whose design requires knowledge from all studied courses, such as proper technical writing from a technical communication course or force analysis from a dynamics course. These projects are not a course in themselves, with no scheduled lectures or laboratories; rather, they are part of all courses. Students undertake them outside scheduled class hours, with project grades being given through all contributing courses. About 25% of marks for the contributing courses are given through the integration projects.

This level of integration requires an immense amount of coordination. The University of Sherbrooke manages it by implementing teaching teams for each term with proactive feedback mechanisms. Teaching teams consist of all faculty members teaching a course within a particular term. In addition to their normal teaching course load, the teaching teams participate in three weekly meetings. The first is with all students in all courses to review the concepts covered during that week. The second meeting is with select student representatives to receive feedback on how well the concepts for that week

were understood. The third meeting is with the teaching team alone to review the student feedback and plan the following week of instruction [F. Charron & D. Proulx, personal communication, October 17, 2006; 14].

4. Conclusions

Many universities in Canada and the United States have expanded engineering design beyond the fourth-year capstone course and into the first year. Though perhaps not as technically proficient as their senior counterparts, first-year students can and are taking on challenging and meaningful engineering design projects. From designing and building prototypes for industry clients, to creating assistive technologies for non-profit organizations, first-year students are capable of making an impact. Some universities have allocated as much as 25% of their first-year programs to resource-intensive engineering design courses.

Compared with engineering science subjects, in which methods of instruction are remarkably uniform from university to university, the wide variation in engineering design instruction methods is striking. In part, this variation is due to the different resource constraints and priorities at each university. These engineering design courses can be implemented using their own custom set of six common instructional methods: full-scale project, small-scale project, case study analysis, reverse engineering project, design tools and methods instruction, and integration.

A growing number of universities in Canada and the United States are dedicating significant resources to the implementation of engineering design courses in the first-year. Universities considering doing the same should take care to review the various design instruction methods used in the first-year to make an educated decision on which methods are best suited to their university.

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