Curriculum as an Engineering Design Problem

by

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Abstract

If the teaching of engineering is indeed the practice of engineering, then it stands to reason that the development of engineering curricula can be treated as an engineering design problem. In this paper, the authors apply the engineering design process to develop a list of courses, for a Mechanical Engineering Program, that conforms to the constraints of the Canadian system of engineering accreditation. For the purpose of this exercise, the following steps are used to define the engineering design process: identical and delimit the problem, establish the outline of the solution (and alternatives), break the problem into its constituent parts, analyze the parts, synthesize the parts into a final configuration, and document the solution. The limits and constraints on the solution are based on the criteria specified by the Canadian Engineering Accreditation Board (CEAB), the syllabus specified by the Canadian Engineering Qualifications Board (CEQB), some common rules-of-thumb, and previously published work by the authors. By utilizing the engineering design process, schools of engineering and applied science can ensure that their curricula, at least at the level of the course specification, will conform to the CEAB and CEQB requirements. As a final exercise, variations on the curriculum are studied to analyze the possibility of introducing such additional elements as options and minors, expanded studies in the arts and humanities, and

development of skills in additional languages.

I. Introduction

Curricula for most engineering programs have evolved; they have not been designed. Even at new schools and for new programs, where there has been opportunity for detailed curriculum design, the programs are generally based on existing programs at other schools or on variations of existing programs at the same school. These are not statements of criticism, simply statements of fact. In many ways, the development of curricula mirrors the development of engineering design standards.

For the purpose of this paper we will define two types of engineering design. We will use the term "formal engineering" to describe engineering design that conforms to a legislated code. Structural system, mechanical system, and electrical system design are the arch-typical examples of this type. We will use the term "non-formal engineering" to describe the type of design that is not based on a legislated code. Much of the design of commercial products by corporations is of this type. Formal engineering in virtually all cases has evolved from non-formal engineering. As a field of engineering matures, or if public safety is an immediate concern, best practices become standardized, often by professional interest groups, then the

standards become codified by legislative bodies. We contend that engineering curricula have been developed by non-formal engineering methods. But there are now in Canada documents from the Canadian Engineering Accreditation Board (CEAB) [1] and the Canadian Engineering Qualifications Board (CEQB) [2] that can form the basis of a more formal design process. These documents are of the "standard" variety not the "code" variety. We want to be clear that this paper in no way encourages a move to a codified system.

Regardless of the formal or non-formal nature of engineering design, all engineering design proceeds by means of the engineering design method. There are perhaps as many descriptions of this method as there are writers about it (see [3]). For the purpose of the present paper we will assume that this method proceeds by the following steps:

- Step 1 . Identify and delimit the problem.
- Step 2. Establish the outline of the solution (and alternatives).
- Step 3. Break the problem into its constituent parts.
- Step 4. Analyze the parts.
- Step 5. Synthesize the parts into a final configuration.
- Step 6. Document the solution.

In the present paper, the engineering method will be used, in a semi-formal engineering design process which utilizes the published criteria of the Canadian Engineering Accreditation Board (CEAB) and the Canadian Engineering Qualifications Board (CEQB) as standards, to design a Mechanical Engineering Program. In Canada, CEAB is the body that accredits engineering programs. If a student graduates

from an accredited program, he/she is considered to be academically qualified to become an Engineer-in-Training. CEQB is a body that develops syllabi for engineering disciplines; these syllabi are used to develop examination programs for applicants to the profession who do not hold an accredited degree. The CEQB criteria are more prescriptive than are the CEAB criteria, containing much detail on course content. Further, whereas every accredited engineering program in Canada must meet the CEAB criteria, there is no formal need to meet the CEQB, criteria. The accreditation system relies on the expertise of program visitors to ensure that programs contain the appropriate course content. In the following, the CEQB criteria will be used primarily to specify course titles.

II. The Design of a Curriculum

Step 1: Identification and Delimitation of the Problem

The design objective (the identification of the problem) is as follows:

"To design a Mechanical Engineering Program that conforms to the published criteria of CEAB and CEQB."

The limits of the problem are listed below; these limits represent a summary of the CEAB and CEQB criteria. For each of the present criteria, a reference to the CEQB or CEAB section/criterion is given. The interested reader is referred to the documents for more detailed information, particularly in the case of the CEQB material.

1. The program must contain appropriate elements of the following (CEQB 2.2):
 - a) mathematics

- b) probability and statistics
 - c) computing
 - d) physics
 - e) chemistry
- 2. The program must contain appropriate elements of the following complementary studies (CEQB 3. 1):
 - a) engineering economics
 - b) engineering in society (including health, safety, and the environment)
 - c) management concepts for engineers
- 3. The program must include elements of appropriate basic and engineering sciences. CEQB requires competency in six of the following twelve topics (CEQB 3.2):
 - a) statics and dynamics
 - b) electrical circuits and power
 - c) advanced mathematics
 - d) mechanics of materials
 - e) mechanics of fluids
 - f) digital logic circuits
 - g) basic electromagnetics
 - h) thermodynamics
 - i) properties of materials
 - j) organic chemistry
 - k) biology
 - l) geology
- 4. The program must contain appropriate elements of the following engineering sciences (CEQB 4.12. 1):
 - a) applied thermodynamics and heat transfer
 - b) fluid mechanics and applications
 - c) kinetics and dynamics of machines
 - d) advanced strength of materials
 - e) design and manufacture of machine elements
 - f) electrical and electronics engineering
- 5. The program must contain appropriate elements of engineering science at an advanced level. CEQB requires competency in three of the following nine topics (CEQB 4.12. 1):
 - a) advanced machine design
 - b) environmental control in buildings
 - c) energy conversion and power generation
 - d) system analysis and control
 - e) production planning and manufacturing
 - f) fluid machinery
 - g) aerodynamics of flight
 - h) aircraft materials and structures
 - i) and finite element analysis
- 6. The program must contain a minimum of 420 AU of combined appropriate mathematics and natural science (CEAB 2.2.4).
- 7. The program must contain a minimum of 195 academic units (AU) of appropriate mathematics (CEAB 2.2.2).
- 8. The program must contain a minimum of 195 AU of appropriate basic sciences (CEAB 2.2.3).
- 9. The program must contain a minimum of 900 AU of combined appropriate engineering science and engineering design (CEAB 2.2.4).
- 10. The program must contain a minimum of 225 AU of appropriate engineering science (CEAB 2.2.4).
- 11. The program must contain a minimum of 225 AU of appropriate engineering design (CEAB 2.2.4).
- 12. The program must contain a minimum of 225 AU of appropriate complementary studies (CEAB 2.2.5).

13. The entire program must contain a minimum of 1800 AU (CEAB 2.2.6).
14. The program must include engineering sciences that impart "an appreciation of related engineering disciplines" (CEAB 2.2.4).
15. The program must culminate in a "significant design experience" (CEAB 2.2.4).
16. The program must contain appropriate content requiring the application of computers (CEAB 2.2.4).
17. The program must include material on engineering economics, the impact of technology on society, and subject matter related to the "central issues, methodologies and thought processes of the humanities and social sciences" (CEAB 2.2.5).
18. The program must contain provision to develop the language skills of students, both oral and in writing (CEAB 2.2.5).
19. The program must contain appropriate laboratory experience (CEAB 2.2.7).
20. The program must ensure that students are aware of the role and responsibilities of engineers to society, "ethics, equity, public and worker safety and health considerations and concepts of sustainable development and environmental stewardship" (CEAB 2.2.8).

These 20 criteria will serve as our design limits (constraints). The CEAB and CEQB documents may be treated as two parallel but non-consistent standards. They are in some cases overlapping (e.g. 1c with 16) but in no case are they contradictory. In the present exercise, we will attempt conformance with all 20 constraints.

In addition to standards, engineering design is based on "rules-of-thumb," often undocumented practices that are "expected" to be conformed to. For our purposes, we will utilize three such rules-of-thumb:

1. In practice, the "expected" value for programs is at least 2000 AU. The 1800 AU minimum is an absolute minimum and not a goal to aim for.
2. In some cases, an assigned CEQB exam in the area of engineering science can be replaced by taking two university level courses containing the appropriate material.
3. The "Norris rule" that requires very critical examination of any category for which the AU count is less than 5% over the minimum requirement (a factor of safety of 1.05).

Step 2: Establish the Outline of the Solution

In order to apply the limits, the AU must be defined. Following CEAB Criterion 2.2.1, an AU is awarded for each 50-minute period of lecture instruction and each two hours of laboratory/ tutorial instruction. In cases where a course has no formal lectures or laboratories (e.g. thesis courses and some design courses) the AU are assigned based on credit hours. For the purpose of our design, we will assume a "standard course" with three 50-minute lectures for each of twelve weeks. For mathematics, science, and engineering courses, a total of 24 hours of tutorial/ laboratory (Criterion 20) will be assumed. It follows that complementary studies courses will have 36 AU; mathematics, basic science, engineering science, and engineering design courses will have 48 AU (36 AU + 12 AU). We note that typically design courses, and particularly capstone design courses, do not have many

lectures but have a high number of credit hours, often as many as five. A five credit hour course would have 60 AU.

An outline of the solution is based on the CEAB requirements and the definition of the AU:

1. 195 AU of mathematics @ 48 AU per course suggests a minimum of 5 courses.
2. 195 AU of basic sciences @ 48 AU per course suggests a minimum of 5 courses.
3. 420 AU of combined mathematics and basic science @ 48 AU per course suggest a minimum of 9 courses.
4. 225 AU of engineering science @ 48 AU per course suggests a minimum of 5 courses.
5. 225 AU of engineering design @ 48 AU per course suggests a minimum of 5 courses; 60 AU suggest a minimum of 4 courses.
6. 900 AU of combined engineering science and engineering design @ 48 AU per course suggests a minimum of 19 courses.
7. 225 AU of complementary studies @ 36 AU per course suggests a minimum of 7 courses.
8. 1800 AU of total content suggests a minimum of 40 course (7 @ 36 and 33 @ 48).
9. 2000 AU of total content suggests a minimum of 44 course (7 @ 36 and 37 @ 48).

The above outline suggests that the CEAB criteria be met by clearly defined courses, that is, that courses are all design, or all basic science, or all engineering science. This is not necessarily the case. For example, many courses combine engineering science and engineering design. Furthermore, there is much argument as to

the nature of such topics as thermodynamics. Is it a basic science or an engineering science? In this paper we will avoid this problem by lumping the content into nominal courses. How the courses are actually taught and packaged will not be specified. For example, it makes no difference for two courses if one is all engineering science while the other is all engineering design, or if both are half engineering science and half engineering design.

The criteria for AU in the five categories (mathematics, basic science, engineering science, engineering design, and complementary studies) can be met by a total of 36 courses. This means that the CEAB criteria can be accommodated and still leave between 4 (if a total of 40 courses are specified) and 8 (if a total of 44 courses are specified) courses completely unconstrained by the detailed criteria but required by the criteria for 1800-2000 AU overall. In fact, many Canadian engineering programs are based on 48 courses. In these cases, the CEAB criteria can be satisfied and still leave 12 (that is, 48 courses minus 36 courses) courses for creative curriculum programming,

The CEQB criteria suggest a total of 23 required topics. Using the second rule-of-thumb, this suggests 46 courses, a number in close agreement with the 2000 AU count of the first rule-of thumb and the typical 48 course program. (This is not strictly true because some of the basic science topics may be covered by a single course, while the mathematics topics may need three or four courses. However, this estimate is approximately true.) The CEQB is still not particularly restrictive because 9 of the topics can be chosen from fairly extensive lists.

Step 3: Break the Problem into its Constituent Parts

This part of the design process has already been done for us by the CEAB criteria. The parts are simply the AU categories: mathematics, basic sciences, engineering sciences, engineering design, and complementary studies. Each of these components must be designed to accommodate the non-numeric CEAB criteria and the CEQB criteria.

Step 4: Analyze the Parts

Mathematics

Although four courses marginally meets the CEAB criteria, the third rule-of-thumb and good engineering practice requires a margin of safety. Furthermore, the demands of the engineering science course material in mechanical engineering require the following mathematics courses: four calculus courses (including partial differential equations), a course in linear algebra/vector analysis, and a statistics course. This leads to six courses. These courses provide ample opportunity to satisfy Criteria 1a, 1b and 3c. The AU for mathematics would be 288, well over the 195 minimum.

Basic Sciences

Four courses are required in the category of basic sciences. It is our opinion that a properly educated mechanical engineer would require classical physics, modern physics, physical chemistry, and advanced chemistry including elements of organic chemistry. The requirement for the fifth courses is satisfied by many Canadian engineering programs by including elements of thermodynamics, statics and dynamics, fluid mechanics, properties of materials, and

even heat transfer as "basic sciences." Such practices often lead to disagreements with visiting accreditation teams, and can lead to violation of the third rule-of-thumb. In order to avoid this possibility, we will specify a free elective in basic science as our fifth course. A mechanical engineer could profit from many basic sciences including biology, ecology, organic chemistry, and geology. These courses provide ample opportunity to satisfy Criteria 1d, 1e and 6, as well as 3j, 3k or 3l. The AU for basic sciences would be 240, well over the 195 minimum.

Engineering Sciences

Hopefully, there is no engineering program in the world that is based on only five courses in engineering science. Therefore, the CEAB criteria will be easily exceeded. In the context of Criterion 14, it is our belief [4] that all engineering programs should include basic courses in the three foundation engineering sciences: statics and dynamics, electrical circuits, and thermodynamics. These courses satisfy Criteria 3a, 3b and 3h. Beyond this, we suggest the following courses: a) two courses in fluid mechanics (Criteria 3e and 4b) b) two courses in materials science (Criterion 3i and 4d) c) two courses in mechanics of materials (stress analysis) (Criterion 3d and 4d) d) two courses in electrical systems (power and digital) (Criteria 3f, 3g and 4f) e) one course in numerical methods (including finite element or finite difference) (Criterion 5i) f) three courses in mechanics of machines, machine design and component manufacture, including CAD (Criteria 4c, 4d and 4e) g) one course in measurement and controls (Criterion 5d) h) two courses in advanced thermodynamics and heat transfer (Criterion 4a) i) one course in computing (Criterion 1c). In order to help satisfy Criterion 5, an additional three advanced courses would be required. This totals 22

courses for 1056 AU. Many of these courses will include components of engineering design so that not all of the 1056 AU will contribute to the engineering science component. However, the 225 AU criteria will be easily exceeded and Criterion 10 will be satisfied.

Engineering Design

Engineering design is always the most problematic of the AU categories to satisfy. The basic reason for this is that engineering design is not well defined. There are those that believe that the criteria for engineering design is not satisfied unless "blueprints and parts lists" can be produced. Others believe that simply including "Design" in the title of an analysis course is sufficient to satisfy the criteria. We use a simple criterion to identify design. If there can be more than one answer to a problem, then there must be some level of design involved. In essence, "open-ended" problems are design problems. As a simple example, if a beam of specified shape spans a space, a load is prescribed, and one is asked to calculate the deflection in the beam, that is analysis. If however, the load and the space are specified and one is asked to prescribe a beam that will have less than a given deflection, that is design. Beams with different combinations of shape, size, and material can all satisfy the problem.

The criteria for design is usually satisfied by identifying components of engineering science courses that have a design nature, and adding to this the contribution of the required "capstone" design course (the "significant design experience"). It is our opinion that we should instead develop a core of specialized design courses. These courses should address the criteria related to the responsibility of the engineer and the requirements of occupational health and

safety, and furthermore ingrain the engineering design process, past practice, environmental stewardship, sustainability, and implementation of codes in the education of all engineers. Therefore we propose four design courses be included in the curriculum. In combination with the design content in the engineering science courses, there is ample opportunity to satisfy Criteria 11; the AU for design in the four specialized courses alone would be 192 to 240 depending on the credit hours assigned. Criteria 2b, 2c, 15, 20 and part of 17 would also be satisfied by the four specialized design courses.

Complementary Studies

There remains a collection of at least seven courses to satisfy various criteria related to complementary studies. These will include an engineering economics course (Criterion 2a), a group of three courses that should be taught by humanities or social sciences professors and must include aspects of technology and society and ethics, two courses in communications (one preferably taught out of an English department). (Communications would also be emphasized in the four design courses and throughout the laboratory components in the preparation of laboratory reports.) This last collection would satisfy Criterion 17. A course in project management would satisfy Criterion 2c, although this material can easily be accommodated in the design series. Criterion 12 would then be satisfied.

The above analysis identifies 43 courses to satisfy the various criteria. All criteria are fully satisfied except perhaps Criterion 5. This criterion is present to allow "options" or specializations to be developed in mechanical engineering programs. Assuming a total of 48 courses, there is ample opportunity to satisfy this criterion.

Step 5: Synthesize the Parts into a Final Configuration

This part of the design exercise would involve the sequencing of courses and the definition of prerequisites. It is beyond the scope of the present paper.

Step 6: Document the Solution

This part of the design exercise would involve three components: preparation of detailed course outlines that substantially honour the detailed descriptions of topics given in the CEQB criteria; preparation of calendar entries, and submission of an AU analysis to CEAB for accreditation purposes. Again, it is beyond the scope of the present paper.

Step 7: Variations on the Theme

It has been said that the restrictions placed on curriculum content by CEAB prevents schools from being innovative. In the context of the above analysis, this criticism is unfounded. Allowing two courses to satisfy the CEQB specialization criterion (Criterion 5) would still leave up to three courses in most programs. For example, in combination with other courses prescribed in the program, there is ample opportunity to develop a program that meets the entrance requirements of other professional programs such as medicine, dentistry, and law. Further, if the requirements of Criterion 5 are not fully met, a package of up to six courses could be used to develop proficiency in a second language.

Fundamental to the above analysis is the idea of "traditional" courses. Even in this context, flexibility exists to be creative. For example, a specialized two-course package could be developed to cover the material in

statics, dynamics, thermodynamics, and electrical circuits. There is also opportunity to develop courses in the area of mathematics that cover the required material in fewer specialized courses with some of the required mathematical skills being developed as needed in the engineering science courses. It should be possible through careful detailed design to have as many as 8 courses "left over" after meeting the criteria. These courses can be used freely to meet any innovative purpose. In most universities, a "minor" typically constitutes only 6 courses.

Conclusions

In this paper it has been demonstrated that the development of engineering curricula can be addressed by the engineering design process. Using this method, a flexible curriculum that fully satisfies both CEAB and CEQB criteria, has been developed. We contend that by developing a curriculum by a process that is fully informed by the CEAB and CEQB criteria, more flexibility, not less flexibility, will be introduced into programs.

References

1. -, Accreditation Criteria and Procedures, Canadian Council of Professional Engineers, 2001.
2. -, Canadian Engineering Qualifications Board Examination Syllabus, Canadian Council of Professional Engineers, 1998.
3. Koen, B.V., Discussion of the Method for Rightly Conducting the Engineer's Approach to Problem Solution, Oxford Press, TBP.

4. Ruth, D.W., "What is Engineering?", Canadian Conference on Engineering Education, Victoria, British Columbia, CANADA, August, 2001.

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