# Towards a Blueprint for Educating Design Engineers: Design Competency

Version 7.0

NSERC Chairs in Design Engineering and Chairs in Environmental Design Engineering

February 21, 2005

## LIST OF ABBREVIATIONS

| | |
|---|---|
| AACE | The Association for the Advancement of Cost Engineering |
| ABET | Accreditation Board for Engineering and Technology |
| CAD | Computer-Aided Design |
| CAE | Computer-Aided Engineering |
| CCPE | Canadian Council of Professional Engineers |
| CDE | Chairs in Design Engineering |
| CDIO | Conceiving, Designing, Implementing and Operating Real-world Systems and Products |
| CEAB | Canadian Engineering Accreditation Board |
| CPM | Critical Path Method |
| CSA | Canadian Standards Association |
| DFX | Design for X, where X can be any one of cost, reliability, environment, or a combination thereof |
| EAC | Engineering Accreditation Commission |
| FMEA | Failure Mode and Effect Analysis |
| FTA | Failure Trend Analysis |
| HAZOP | Hazards and Operability Techniques |
| IP | Intellectual Property |
| ISO | International Organization for Standardization |
| MEQ | Ministère de l'Éducation du Québec (Quebec's Department of Education) |
| NSERC | Science and Engineering Research Canada |
| SAE | Society of Automotive Engineers |
| SCAMPER | Substitute, combine, adapt, modify, put to another use, eliminate, reverse |
| TIDEE | Transferable Integrated Design Engineering Education |
| TRIZ | Theory on Inventive Problem Solving |
| TUG | TriUniversity Group |
| WHMIS | Workplace Hazardous Materials Information System |

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# Preface

NSERC has recognized the need to improve the quantity and quality of design engineering training in Canada. NSERC's Chairs in Design Engineering and Chairs in Environmental Design Engineering meet twice a year to discuss issues of common interest and review progress.

A focus of these chairs meetings has been addressing the question "What are the competencies that define design engineering?" Over the past two years, the group has explored this question, with a particular reference to existing work. The work of this group on the question of engineering design competencies is presented in this white paper for reference and comment.

Although NSERC supports these chairs, NSERC is in no way responsible for the content presented—credit and responsibility lie with the chairholders involved: Jorge Angeles (McGill), Liuchen Chang (UNB), Ron Britton (Manitoba), François Charron (Sherbrooke), Peter Gregson (Dalhousie University), Peihua Gu (Calgary), Stephan Lambert (Waterloo), Peter Lawrence and Helmut Prion (UBC), Warren Stiver (Guelph), David Strong (Queen's), Paul Stuart (École Polytechnique) and Brian Thompson, whose collaboration during his tenure as NSERC Design Engineering Chair Holder at the University of Western Ontario, is duly acknowledged.

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# Chapter 1

# Introduction

## 1.1 Background and Significance

Increasing global demand for better products and processes in various aspects is apparent: functionality; higher quality; lower costs; higher product customization; easier servicing; reuse and recycling of materials and other energy and environmental challenges. This demand requires that Canadian industry and society be more innovative and responsive in order to stay competitive internationally. Canadian capability in engineering design is at the very core of our ability to achieve this goal.

In the 1990's, the Natural Sciences and Engineering Research Council of Canada (NSERC) conducted nation-wide consultations as to how Canada was addressing these challenges through education, and research and development.

It became apparent that Canadian engineering schools enjoy a strong research culture and have an excellent reputation for research originality, quality and productivity. However, to translate these research results into products and services that benefit the Canadian economy, a design and innovation culture complementing the research culture is necessary. This culture should provide a platform for the integration of research and innovation through engineering design. At both the undergraduate and graduate levels, we must improve the capability and capacity of engineering graduates so that they are capable of leading innovation, and converting research results into value-added products and services. Canadian engineering faculties should seize the opportunity to emphasize engineering design to a greater extent, and cultivate an innovation culture.

In 1999, a new NSERC chair program was created in design engineering; the chair holders of the program would be charged with the responsibility to promote and help enhance design education and innovation at Canadian universities. To this end, the Design Chair Group undertook an initiative to examine engineering design competency as the first step toward a blueprint for the education, in the Canadian education system, of capable design engineers.

## 1.2 Motivation and Objectives

Canadian engineering schools have been producing high-quality engineering graduates for many years. Canada has accreditation processes that are arguably among the highest of engineering standards in the world. Further enhancement of our engineering education programs depends on the criteria that we, as professionals, articulate to address the increasing and emerging challenges that Canadian society is facing today, but were not so critical a few decades ago.

The main objective of this document is to define the *design competency*, from which universities may draw inspiration in the development of new and innovative engineering education programs, so that Canada can produce highly qualified engineers with a strong capability to lead innovation.

## 1.3 Process

At the very outset of the Chairs in Design Engineering (CDE) Program, NSERC and the chair holders in design engineering jointly decided that it was high time to initiate an annual monitoring of the activities of the various chairs by means of regular meetings. These meetings would provide an opportunity to share the results of the training and research experiences of the chairs promptly. The first meeting was held in June 2002 in Ottawa.

During this meeting, a number of fruitful exchanges allowed the NSERC design chairs to share the results of their respective projects. It was quickly observed that having a collective language would be of value for: discussing design; facilitating exchanges; and, more importantly, helping to put forward a vision of design to universities, professional associations, certification offices, manufacturing companies, service companies, and other stake-holders. Therefore, it was decided to hold theme meetings every six months to discuss topics directly related to engineering design.

The first theme meeting was held at the University of Sherbrooke in December 2002, under the theme *engineering design competency*. All chair holders presented papers on the topic. While the presentations reflected the personal perspective of each chair holder, they also included bibliographic research and interviews with colleagues and people from industry. At the end of this first meeting, participants agreed to revisit the topic at the chair holders' annual meeting in June 2003 at the University of Calgary. The objective of the second discussion about design and design competency was the synthesis of the documents presented during the December 2002 meeting and the initiation of a paper defining design and design competency. The follow-up meetings in Calgary, Montreal and Halifax continued the discussions.

This document is the result of these theme meetings about the engineering design competency held up to the Halifax meeting on July 5 and 6, 2004.

## 1.4 Document Outline

Chapter 2 provides a general background of engineering design in the context of engineering education in Canada. First, we examine some of the current accreditation approaches and focus on the ones concerning engineering design education. Second, various issues and challenges are addressed, the focus being undergraduate engineering education in general, and engineering design education in particular.

Chapter 3 examines some of the fundamental questions related to engineering design and the profession, which can be used as a basis for articulation of the design competency. After addressing some of these fundamental questions, a comprehensive review of the engineering design competency literature is included in Chapter 4. Based on these studies and consultations with our industrial partners, we propose in Chapter 5 a definition of engineering design competency.

The document ends with conclusions, including a proposal for future work.

# Chapter 2

# Overall Context of Engineering Design Education in Canada

## 2.1 Accreditation

Engineering associations in many countries have established accreditation mechanisms to evaluate and accredit the undergraduate engineering programs of education institutions to ensure that standards acceptable for professional engineer registration are met, and that the quality and relevance of engineering education continuously improve. Accreditation is usually a voluntary, non-governmental process of peer review. It requires an education institution or program to meet certain defined standards or criteria. In Canada, the Canadian Engineering Accreditation Board (CEAB), a standing committee of the Canadian Council of Professional Engineers (CCPE), has been responsible for the accreditation of Canadian engineering education programs since 1965. The United States' CEAB counterpart is the Accreditation Board for Engineering and Technology (ABET), which is responsible for the accreditation of engineering and technology education programs. In general, a country's professional engineering association is the accreditation organization for its engineering programs.

In Canada, 36 educational institutions offer accredited undergraduate engineering programs leading to an engineering degree at the bachelor's level. There are currently 236 accredited engineering programs in a wide range of engineering disciplines. In addition to the general engineering disciplines such as civil, electrical, mechanical, chemical, industrial, manufacturing, materials and computer engineering, there are also accredited programs for specific sectors and disciplines such as aerospace, agricultural, bioresources, mining, building, ceramic and forest engineering. Since the 1990's, several new engineering programs have been accredited, representing newly developed disciplines and multi-disciplines.

### 2.1.1 CEAB Accreditation Criteria

The accreditation of undergraduate university engineering programs in Canada dates back to 1965, and is undertaken for CCPE by the Canadian Engineering Accreditation Board. In order to be accredited, an engineering program must meet or exceed the accreditation criteria established and published by CEAB annually. The criteria are both quantitative and qualitative, with emphasis on the quality of the students, academic staff, support staff and educational facilities. The criteria have evolved over the years to reflect such issues as technological advances and the growth of the engineering team in the workplace. In recent years, CEAB has implemented changes in the accreditation criteria (CEAB, 2002; De Bon *et al.*, 2002), such as:

- refining the curriculum content requirements for basic sciences and mathematics;
- including morale and commitment of faculty, support staff and students as a component of the qualitative evaluation; and,
- requiring that students be exposed to the concepts of project management.

Accredited engineering programs must include not only adequate mathematics, sciences and engineering content, but also adequate complementary studies that deal with central issues, methodologies and thought processes of the humanities and social sciences. Programs must also allow students to develop communication skills, and an understanding of the concept of sustainable development and of the environmental, cultural, economic and social impacts of engineering on society. The quantitative criteria for curriculum content assure a foundation in mathematics and basic sciences, a broad preparation in engineering sciences and engineering design, and an exposure to non-technical subjects that complement the technical aspects of the curriculum (CEAB, 2002).

Appropriate laboratory experience must be an integral component of the engineering curriculum. Each program must also ensure that students are made aware of the role and responsibilities of a professional engineer. Appropriate exposure to ethics, equity, public and worker safety, health considerations, and concepts of sustainable development and environmental stewardship must be part of the engineering curriculum. The program must prepare students to learn independently and must expose them to engineering research and development or other innovative engineering activities.

In addition to quantitative criteria, CEAB also places a strong emphasis on the quality of the educational experience, as reflected by the quality of the administration, laboratories, library, and computing and other supporting facilities; and by the quality, morale and commitment of the faculty, support staff and students. The number of faculty devoted to the program must be large enough to cover all curricular areas. The faculty who teach courses in the engineering curriculum are expected to have a high level of competence and to be dedicated to the aims of engineering education. Individuals teaching primarily engineering sciences and design courses are expected to be registered professional engineers in Canada.

Changes to accreditation that are under consideration at CEAB, for future accreditation of engineering programs in Canada, include (De Bon *et al.*, 2002):

- enhancing outcome-based assessment features;
- modifying the options available to universities following a denial of accreditation;
- improving the term 'Complementary Studies' to better reflect the essential nature of these skills; and,
- revising the "Advanced Standing, Prior Studies and Exchange Studies Regulations" document, which is a supplement to the CEAB Accreditation Criteria and Procedures.

### 2.1.2 Trends in Engineering Accreditation

Engineering education has been responding to technological advances, political and economic realities, the job market and public interest. As a quality-assurance program, engineering accreditation is also evolving. The trends below have been observed in engineering accreditation in recent years.

#### Outcome Assessment

Many engineering accreditation organizations outside Canada, particularly those in industrial countries such as the United States, Australia, Japan, and in the European Union have focused on **outcome assessment for quality assurance** in the assessment of engineering programs. In its "Engineering Criteria 2000", the United States' ABET shifted away from a traditional prescription of what engineering programs should be like, toward examining the outcomes of engineering education. The old criteria set standards for factors like faculty size, curricular requirements, and the quality of laboratories and other facilities. The new criteria focus more on the educational objectives of engineering programs and the evaluation procedures to ascertain whether objectives are met. Engineering programs must demonstrate that their graduates have the ability to: apply knowledge of mathematics, science and engineering; design and conduct experiments; analyze and interpret data; **design a system, component, or process to meet specified needs**; function on multidisciplinary teams; and, identify, formulate and solve engineering problems. Engineering graduates must also have: an understanding of professional and ethical responsibilities; an ability to communicate effectively; the broad education necessary to understand the impact of engineering solutions in a global and societal context; a recognition of the need for, and an ability to engage in, life-long learning; a knowledge of contemporary issues; and the ability to use the techniques, skills, and modern engineering tools necessary for engineering practice (ABET, 2001).

#### Engineering Design

Under outcome-based criteria, accreditation organizations have emphasized engineering design as a key component. ABET requires programs to include 1.5 years of engineering topics, consisting of engineering sciences and engineering design appropriate to the student's field of study. In Canada, CEAB specifies a minimum of 225 academic units for engineering design[1] and expects that the faculty teaching engineering science and engineering design be registered professional engineers.

In Australia, the structure and content of an engineering program must ensure that its graduates acquire attributes including the ability to undertake problem identification, formulation and solution, and to utilize a systems approach to design and operational performance. Specifically, engineering design and projects should be about 20 percent of the total program content in a typical four-year program.

In Europe, due to cultural diversity and a long history of education, engineering accreditation and the treatment of engineering design have taken various forms and approaches; however, engineering design is not emphasized in the accreditation process. In Japan, engineering accreditation requires that a program establish and disclose concrete learning and educational objectives, including design abilities, in order to organize comprehensive solutions to societal needs by exploiting various disciplines of science, as well as various types of technology and information. Similar

[1] The 225 AU for engineering design represents 12,5% of the overall program and engineering design together with engineering sciences must be 900 AU

to CEAB, Japan specifies quantitative curriculum requirements in which engineering design is regarded as an important element for certain engineering programs.

### Internationalization

Globalization has been an undeniable phenomenon in engineering professions, as marked by the international mobility of practicing engineers and students. More and more educational institutions have signed agreements of collaboration with institutions of other countries. In most engineering faculties, international students have become an integral part of the student body. Along with these developments, international agreements on engineering education, accreditation and practice have been developed. One of the first agreements was signed in 1980, by the CEAB and the Engineering Accreditation Commission (EAC) of ABET, where the two parties mutually recognize the graduates of all engineering programs accredited by each party. A much broader mutual recognition agreement, entitled "Recognition of Equivalency of Engineering Education Courses/Programs Leading to the Accredited Engineering Degree," also known as the Washington Accord, was developed several years ago. Several countries or regions, including Australia, New Zealand, Canada, the United States, Ireland, the United Kingdom, Hong Kong and South Africa, were signatories of the Accord. In June 2003, Germany, Malaysia and Singapore were admitted as new members. Several other countries are currently in discussions to join the Washington Accord. Kuwait, the United Arab Emirates and other Middle-East countries have used ABET criteria for external assessment of their engineering programs.

### New and Innovative Programs

Rapid development in technology has led to the formation of numerous new engineering disciplines. Employers are now demanding engineers with special skills in these disciplines. Accreditation organizations have responded to the needs of the engineering community by accrediting these new engineering programs. Disciplines accredited in the past decade include computer engineering, geomatic engineering, oil and gas engineering, software engineering and environmental engineering. Other newly accredited engineering programs have emerged from multidisciplinary work, such as chemical and biological engineering, engineering systems and computing, chemical-civil-computer-mechanical-manufacturing engineering, etc. It is expected that, in the future, more innovative engineering education programs will be developed and accredited.

### Partnership in Education

Interactions and partnerships between engineering schools and outside stake-holders, such as industry, and engineering organizations and associations, have been rapidly developing and strengthening. The partnerships in engineering education have been ongoing in two areas: (*i*) providing engineering students with real-world practical experience as an integral part of their academic program; and (*ii*) inviting practicing engineers onto advisory and decision-making bodies that control the engineering curriculum. This trend has changed the curriculum and delivery of engineering education, accelerated the emphasis on engineering design and project-based learning, and promoted the inclusion of "soft" skills such as communications, teamwork and project management.

## 2.2 Strategic Issues in Engineering and Engineering Design Education

Canadian engineering education has been successful at producing graduates who, over time, have contributed to Canada's high standard of living. However, engineering education must continue to advance, due to the rapid pace of change in engineering and technology (Bell, 2000), the increasingly competitive global economy and the growing pressure on the social and environmental dimensions of quality of life.

Engineering education was largely practice-oriented from its inception through to the middle of the 20th century (Crawley, 2002). It was during and after WWII that engineering education shifted its focus to encompass more fundamental and generalizable tools and approaches, spurred by the writings of Dr. V. Bush (Bush, 1945) and the creation of the National Science Foundation. While this shift has led to an explosion of knowledge, it has also had the unfortunate consequence of **disconnecting engineering education from practice** and becoming increasingly focused on engineering science (Crawley, 2002).

There has been a growing awareness of the issues facing engineering education. As far back as 1955, the Grinter Report (Grinter, 1955) *presented* the need to ensure that curricula contain "integrated study of engineering design, analysis and engineering system"; "continuing, concentrated effort to strengthen and integrate work in the humanistic and social sciences"; "an insistence upon the development of a high level of performance in the oral, written and graphical communication of ideas"; and, "the encouragement of experiments in all areas of engineering education." More recent work has confirmed and extended this view to include the need for more multidisciplinary education (Crawley, 2002). One must ask why these needs have not been met for nearly 50 years.

As Bordogna (1997) says: "The engineer must be able to work across many different disciplines and fields. Tomorrow's engineers will need to use abstract and experiential learning, to work independently and in teams, and to meld engineering science and engineering practice."

Tomorrow's engineers must be able to cope with problems and challenges significantly different from their predecessors. The engineering profession should be closely integrated with business and society; engineering students must learn that engineering and engineering design should offer value to both industry and society. An industry-based value proposition is usually easy to quantify: the new solution decreases costs, increases profits or confers a new capability for which there is a demand. A societal value proposition cannot be stated so succinctly, but is often embedded in the regulatory environment in which the engineering graduate and his/her employer operate.

Typically, faculty members in Canadian and U.S. universities do not have significant industry experience. On the other hand, until recently, 10 to 15 years in industry was the rule in Germany to become an engineering professor (Altan, 2003). Some schools have implemented active programs to engage faculty and students with industry (Denton and Hutzel, 2003), so as to ensure that faculty are familiar with the modern manufacturing environment and current technology.

In the sections below, the major issues and some specific challenges facing engineering education today are discussed. These include: the need for faculty renewal; the structure of engineering programs by discipline and subject; the pace of change; competition; and innovation.

### 2.2.1 Faculty Renewal

Approximately one-third of engineering faculty in tenured or tenure-track positions in Canadian universities are over the age of 50 and, thus, likely to retire within the next 15 years (CCPE, 2003). Overall, undergraduate enrollment increased by nearly 20 percent from 1997 to 2001, and may potentially grow by a further 20–30 percent by 2011 (CCPE, 2003). An adequate supply of faculty, for growth or even replacement, is uncertain.

In the past few decades, the tenure and promotion system has tended to reward archival publications, and not interaction with industry. Faculty at all levels were reluctant to add industrial involvement to their already considerable workload and to place possible restrictions on academic freedom, such as the freedom to publish results (Beaufait, 1997).

The significant turnover of faculty in the near future and the potential need for faculty provides an opportunity for change. Over the next 15 years, the chance exists to transform hiring norms, and promotion and tenure policies. Instead, interaction with industry may be rewarded, in order to attract industrial expertise and to restructure courses to better reflect the teamwork, communication and collaboration skills demanded by industry and society (Grinter, 1955; Denton, 1997; Beaufait, 1997; Bell, 2000).

### 2.2.2 Program Structure by Discipline and Subject

Engineering programs at Canadian universities are structured by broad engineering disciplines and, at times, by sub-disciplines. (CCPE, 2004) identifies approximately 76 different names for actively accredited engineering programs in Canada. Even by grouping these into similar fields, there are still 13 different disciplines. A large number of programs, most of which are highly specialized, simply do not fit easily into any category (CCPE, 2003).

Nearly all 36 Canadian engineering schools are departmentalized. This leads to segregation of faculty and students within discipline boundaries. As a result, academic teams and projects rarely engage students from multiple engineering disciplines or students from outside engineering. As Coates (2000) puts it:

> "The last half or more of the 20th century, however, has found that the world of practical applications is increasingly cross-disciplinary, and even more rapidly becoming interdisciplinary. The integration across fields in the world of practical applications is often delayed until the engineer has moved into a job rather than being part of his or her university education. Universities to meet their obligations to students and to society need to move toward true interdisciplinarity."

The need for true interdisciplinarity is driven by increased local and global competitiveness, both because industry is rewarded for getting to market first (first-mover advantage) and because markets are no longer defined geographically. **To meet this need, product realization has become a more concurrent and less linear process in most companies, requiring a large variety of skills on the part of the design team**. In addition, the greatest rate of innovation and employment is now in small- to medium-sized enterprises. These organizations require employees to have considerable familiarity with all aspects of design. Compartmentalization is no longer an option.

In a survey of 12 UK institutions, the modularization of degrees tended to limit cooperation and make sustaining multidisciplinary projects difficult (Denton, 1997). (King (1995) argues that the fragmentation of engineering disciplines stifles engineering design creativity through "the narrower perspective afforded by a high degree of specialism".

Mechatronics is an example of a genuinely integrated field that is leading to cross-disciplinary work among both faculty and students. Groups from mechanical engineering, electrical engineering and computer science and engineering are overcoming disciplinary hurdles.

Environmental engineering is a truly cross-disciplinary field of engineering practice, relying on the skills of electrical, mechanical, chemical and civil engineering. At some institutions, disciplinary boundaries and battles between departments have led to a more narrowly-defined scope for environmental engineering than would otherwise be appropriate.

The issues surrounding an effective interdisciplinary studies program should not be underestimated. While faculty in many departments are in favour of the approach, hurdles such as scheduling, course prerequisites, and dispersed campuses can create virtually insurmountable obstacles.

Canada's Innovation Strategy (Government of Canada, 2002) points to the "need to encourage cross-training and a multidisciplinary approach, in order to build capacity among MBAs and engineers for the commercialization of these new technologies." This statement refers to environmental and green energy; however, it could equally apply to any innovative technology.

Compartmentalization is also a problem at the course level. Students often fail to see the relevance of some of the material taught in a given course and will not see the connection between courses unless their attention is explicitly drawn to it.

### 2.2.3 The Pace of Technology Changes and Knowledge Growth

The incredibly rapid pace of knowledge growth in engineering poses a challenge to educators. The motivation for increased specialization within engineering is often driven by this growth, while demands for curriculum renewal continue to be addressed by adding content to reflect new fields and new technologies. However, curriculum renewal being a zero-sum game, for every addition, some content must be removed.

The short- and long-term needs of students and employers are often in conflict. If engineering education aims for maximum employment of graduates in the short term, there is generally the risk of providing students with training in the latest CAD software or the use of a particular instrument or process, rather than providing them with a firm understanding of the principles on which these tools rest. However, to ignore the latest technology, the latest software, the latest code or the latest regulatory changes leads to graduates that are out-of-step with engineering practice.

Another consideration is the profound degree to which advances in technology have affected the fundamental philosophy of engineering. Not too long ago, complexity was to be avoided because it inevitably resulted in systems that were fragile and difficult to maintain. The advent of microelectronics, new and advanced simulation tools and advanced CAD has changed this belief. Now, for example, it is standard practice to include microprocessors and advanced electronics in most products, in spite of their complexity. Their inherent reliability, low cost and the toolsets available for their deployment result in more robust, efficient and cost-effective products and processes, which can be brought to market sooner. The advances in computational fluid dynamics, finite element and multi-physics modelling, MEMS, and many other technologies have resulted in similar changes in philosophy for the application domains in which they are used.

### 2.2.4 Competitive Landscape, Accountability Pressures and Costs

Protecting breadth while providing depth within a discipline or subdiscipline has often led to suggestions for a longer-than-four-year engineering degree. However, in the competition to attract students, it is difficult for a university to go it alone. In practice, the average duration of an engineering degree in Canada now runs 4.7 years (CCPE, 2003).

Some schools have been creative in developing programs that extend program duration. McMaster University has succeeded in developing a number of five-year engineering management programs[2]. The positive impact of such programs is still to be measured, but it is probably desirable to integrate engineering and business programs, although scheduling and campus layout of many universities precludes more than a few common courses.

All levels of government and society in general are increasingly looking for evidence of benefits. The Canadian government desires engineers that can increase our standard of living while ensuring that an engineering education is affordable.

Results of a survey conducted by MIT (Crawley, 2002) indicate substantial agreement between the stated needs of industry, alumni and faculty with respect to graduates' capabilities. The only statistically significant difference appeared to be in the area of design, with industry requiring slightly less design competence than either alumni or faculty. The key point of the study, however, **was the substantial agreement on the breadth and depth of both engineering and the "soft" skills required of graduating engineers**. These results are somewhat surprising in the face of considerable evidence (Grinter, 1955; Bordogna, 1997; Bell, 2000; Altan, 2003) that these requirements have not yet been met.

Maclean's "Ranking Canadian Universities"[3] has attracted attention and grown in influence on many campuses. In faculty terms, measurement focuses on the percentage of Ph.D.'s and funding from the major research granting councils. Other important measures for engineering should include: industrial experience; P.Eng. status, and collaboration/funding relationships with industry.

### 2.2.5 Innovation

Engineering program changes in Canada have largely been evolutionary. Over the past 40 years, this evolution has been guided by the Canadian Council for Professional Engineers (CCPE, 1997) through (CEAB, 2002)[4]. The significant faculty renewal that is underway presents an opportunity for innovation and advancement in engineering education, while presenting, at the same time, some risks.

A number of engineering schools have undertaken significant innovations in teaching. Harvey Mudd College (Bright and Phillips, 1999) created, in 1963, the Engineering Clinic, in which student teams, with assistance from several faculty and industry mentors, use real-world carefully selected industry problems. Much of the teaching is centred around this setup, **bringing relevance and a real-world flavour to engineering education**. The University of Western Ontario (Thompson, 2001) has instituted studio-based teaching methods for their engineering design courses. By doing so, students gain real experience with significant, real-world problems and their solutions.

## 2.3 Challenges for Engineering Design Education

A number of issues and challenges are specific to design education. These issues are introduced under a number of themes: faculty, structure and funding. It is important to recognize that the issues identified in the previous section will also influence the capacity of Canadian engineering schools to deliver high-quality design education.

[2] `www.mech.mcmaster.ca/undergraduate/programmes.htm`
[3] `www.macleans.ca`
[4] Refer to section 2.3 for greater detail

### 2.3.1 Faculty

Faculty are the key ingredient in the education process. As repeatedly stressed in this document, engineering design competency relies on knowledge in the design process and experience in designing. A competent engineering design instructor must have lived the design process in real terms.

In North America, engineering faculty members most often establish academic research programs that are heavily focused on engineering science. This strength and emphasis in engineering science has led to an increase in quality and rigour of the engineering science education. This shift was fostered in part by the work of Dr. Bush (1945) and the formation of the U.S. National Science Foundation. Canada has followed a similar course. This success in advancing engineering science must be replicated in engineering design. Indeed, NSERC's Design Chair Program is an important first step. Attracting faculty to engage in design advancements and activities in their non-lecturing time is an effective means of strengthening design education capabilities at the undergraduate and graduate levels.

Denton (1997) indicated that, in a survey of 12 UK institutions, very few faculty had any expertise in team-based design. Development of student-based, multidisciplinary teams was generally led by faculty with team experience and was not supported by their colleagues who lacked this experience. Successful use of multidisciplinary teams often relied on external expertise or support and encouragement from industrial contacts. Gorman *et al.* (2001) reinforced the importance of team skills, stating that, to be successful, team training is needed for faculty.

The substantial faculty renewal that will be occurring over the next 15 years provides an opportunity to attract faculty with engineering design experience. The anticipated shortage of Ph.D. engineering graduates to fill faculty positions may open up hiring to include experienced engineers from industry, consulting and government.

### 2.3.2 Evaluation and Reward System

Tenure, promotion and compensation policies have a dominant role in shaping the activities and priorities of all faculty, but play an especially important role for new faculty. The perception of the academic engineering community is that success in academe is driven by research success, measured largely by the number of refereed journal publications.

Evaluation and reward systems need to be more inclusive. Gorman *et al.* (2001) pointed to modifications necessary to reward industrial experience and to honour collaboration in teaching and research.

Engineering design instruction is recognized as requiring considerably more time for course development, project selection and student consultation. This time investment takes away from time available for research. Many senior faculty members advise new faculty to limit their engagement in design activities, at least until they have tenure, so as to maintain their research productivity on which promotion and tenure rests.

Course loads for team-taught engineering design courses must be computed appropriately, in order to recognize the extra effort required for developing and delivering these courses.

### 2.3.3 Design Facilities

Team-based design and design at large rely on a different mix of educational space than engineering science courses. Design studios, meeting rooms, (machine or equivalent) shop , storage space, advanced software, and large-format printers are just some of the unique needs. Design studios in particular are not commonly found in engineering schools in Canada, although some schools have developed them. The University of Western Ontario has developed studio-based design (Thompson, 2001); Queen's University has the Integrated Learning Centre (2004), the mechanical engineering departments at Sherbrooke University and the University of Calgary have created considerable design facilities and spaces for undergraduate students; McGill University established a Design Studio in the early nineties.

Facilities must include access to appropriate expertise. The Engineering Design Trilogy in the Department of Biosystems Engineering at the University of Manitoba is structured so that senior students can mentor more junior students. In addition, engineers in the Engineers-in-Residence Program bring practical, real-world experience to student design-project teams (University of Manitoba, 2004).

### 2.3.4 Variety of Design Settings

Design settings and problems are not all equal. They differ in style and may rely on quite different approaches.

Design-to-specification captures the setting in which a client or boss explicitly provides the performance specifications of the product. Design in this context often follows established recipes that are available in textbooks and software. Design-to-specification can often be taught within a single course. Graduates of Canadian engineering schools are well respected for their ability to design artifacts once given the specifications.

Design-to-need captures the setting in which a need has been identified and defined. However, the detailed specifications and nature of the product to satisfy the needs are initially unknown. The design engineer has a greatly increased scope of creativity that enables him/her to investigate new and innovative approaches to the problem. Design instruction parcelled into content-specific courses has difficulty addressing design to need. Design-to-need is more integrated and frequently interdisciplinary. Current education approaches struggle in this domain.

Design-for-opportunity is a highly entrepreneurial approach to engineering design. If the design engineer is faced with a potential opportunity, as opposed to a statement of need or a specification, he/she has considerable latitude as to the approach to be taken. This form of design requires considerable knowledge of marketing, business and engineering. At present, Canadian engineering schools are not at all well-equipped to teach design-for-opportunity, although there is some growing interest in this approach (Memorial University of Newfoundland and Labrador, Dalhousie University and the University of New Brunswick have one course that is highly entrepreneurial and is being piloted as a synchronous, distributed learning course via the web at this time.) At least one U.S. school, Olin College, has designed a highly entrepreneurial engineering program (Olin, 2003, 2004).

An analogy to the world of cooks and chefs has been used to illustrate the differences in design-to-specification, design-to-need and design-for-opportunity. Design-to-specification can be thought of as the equivalent of a good cook. A good cook is an individual that follows recipes well and delivers the expected meal to the table. Design-to-need is a much more creativity-based enterprise and may be comparable to a sous-chef, who can create a fine plate with the appropriate seasonings and superb presentation. Design-for-opportunity is the domain of the master chef, who creates a dining experience that is unique to the situation. By appropriately structuring the menu, creating recipes that balance the flavours of the various courses on the palate, selecting the wines and paying attention to the presentation, the master chef develops a product that seizes an opportunity not addressed by those less skilled.

Ultimately, we must be graduating engineers that are certainly good cooks but also beginning chefs.

### 2.3.5 Continuity in Design Education

Many Canadian schools have a first-year design course and a capstone design course. In the first-year course, students tackle a relatively simple problem with considerable assistance from teaching assistants and faculty members. All students work on the same problem, and so they learn from each other. This is an excellent challenge for them at their academic level.

The capstone course is frequently based on projects presented by industry and/or faculty members. Each student team undertakes a different project with the result that the ability to learn from each other is minimized. In this model, students can flounder if their design skills have not progressed sufficiently to handle the degree of open-endedness characteristic of an industry project. They may lack feedback on previous experience.

A number of engineering schools offer a "continuum of design" throughout the curriculum. Harvey Mudd College (Bright and Phillips, 1999) has been offering a sequence of design courses for approximately 40 years. Similarly, all of University of Guelph's engineering programs and the Biosystems Engineering Department at the University of Manitoba have histories of providing series of design courses. The University of Sherbrooke introduced an extensive sequence in the early 1990's. Electrical and Computer Engineering at Dalhousie University has had a continuum of design courses since 1991 (Gregson, 1998).

Providing a design course continuum requires a very large degree of cooperation among departmental faculty members. The provision of an interdisciplinary design course continuum is daunting. The problems associated with ensuring extensive collaboration among faculty members with the requisite expertise are exacerbated by scheduling, resource allocation, space, and registration issues.

# Chapter 3

# Back to Basics

## 3.1 Engineering and Engineering Design

The term 'engineering' is relatively modern, having appeared in French, according to Rey and Rey-Debove (1991), in 1759 as *génie*, a derivative of *ingénieur*. Génie, always followed by a qualifier in European French (génie mécanique, génie électrique, génie chimique, etc.), was introduced to indicate the technical activity in the construction and maintenance of buildings, fortifications, bridges and roads. In another account (Walker, 1987), "The engineering profession as we know it today developed to serve the nonconformist industrialists of the 18th century, who were the midwives of the industrial revolution." Walker goes on to imply that the origins of modern engineering can be traced to the completion of "the world's first iron bridge at Coalbrookdale" in 1779.

In fact, engineering can be regarded as a part of technology. According to Bunge (1983), a body of knowledge is a branch of technology if and only if: a) it is compatible with contemporary science and amenable to validation by means of the scientific method; and, b) it is used to control, transform or produce goods or processes, whether natural or social. Other branches of technology include medicine, pharmacology, agriculture, management, etc. Walker (1987), in turn, identifies engineering as technology itself, and quotes Galbraith, as saying that technology is "the systematic application of scientific or other organized knowledge to practical tasks."

Paraphrasing Glegg (1971), we can say that science is about discovery, engineering about building.

Dictionary definitions of engineering include: "the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people" (Webster, 1997). Engineering is also defined as "conception, étude globale d'un projet industriel sous tous ses aspects (techniques, économiques, financiers, sociaux), coordonnant les études particulières des spécialistes" (Office québécois de la langue française, 2004). This definition can be loosely translated as "The design and comprehensive analysis of an industrial project, considering all its aspects (technical, economic, social, etc.), integrating the work of specialists from various disciplines." In fact, this definition is the same as that found in (Rey and Rey-Debove, 1991); however, it is too limited in that it pertains to the term used in a commercial context. For example, a company providing consulting services usually submits a proposal broken down into various items, one of which is engineering, others being planning, management, and so on.

In summary, then, engineering is a branch of technology. It is a pragmatic activity intended to satisfy human needs, whether physical or intellectual, and its practice is based on sound scientific principles.

### 3.1.1 Engineering Design

The word "design" is derived from the Latin "designare," meaning "to mark out." This word bears many meanings in English: the product, the process, the visual representation, etc.

As a verb, to design is to conceptualize a product, tangible or intangible, intended to satisfy a human need. As a noun, design is a broad concept, including: a) the sublime, e.g., a masterpiece like The Mona Lisa; b) the pragmatic, e.g., a mass transport system; c) the intangible, like a piece of code; and, d) the concrete, like a bridge joining two pieces of land. An architect's view of the subject was provided by Covo (2003):

> "Engineering Design is iterative, creative, at times both analytic and synthetic, and incorporates elements of problem-solving, intuitive and heuristic methodologies. Design is decision-based and goal-directed; designers are presented with problems motivated by human needs related to products, materials and systems of all kinds, and bring to bear rational tools and imagination in methodologies developing optimal solutions."

Engineering design is often said to be problem-solving, and sometimes decision-making, but it is much more, making it difficult to define. However, stating that engineering design is nothing but problem-solving or decision-making is tantamount to claiming that medicine is nothing but prescription-writing. Suffice it to say that:

- engineering design pervades domains, for it occurs in all engineering disciplines—agricultural, civil, chemical, computer, electrical, manufacturing, mechanical, metallurgical, mining, software engineering, etc.;
- engineering design is multidisciplinary, for it resorts to many fields to accomplish its end, the integration of a product; and,
- engineering design is first and foremost synthetic, but may make use of analysis as part of the design process.

The Canadian Engineering Accreditation Board uses a definition of engineering design:

> *Engineering design integrates mathematics, basic sciences, engineering sciences and complementary studies in developing elements, systems and processes to meet specific needs. It is a creative, iterative and often open-ended process subject to constraints that may be governed by standards or legislation to varying degrees depending on the discipline. These degrees may relate to economic, health, safety, environmental, social or other pertinent factors* (CEAB, 2002).

CEAB accreditation documents require the measurement of the proportion of the engineering curriculum that is associated with engineering design. Thus, in Canada, engineering design is an integral part of all engineering programs.

### 3.1.2 Design Engineering

A multidisciplinary design engineering program is devoted to the theory, methods, processes and tools that the engineer uses to create a product satisfying a specific human need, as mandated by the client. Design engineering strives to formulate the general principles on which the design of an engineering product, regardless of the discipline, is based.

In summary, then, engineering design is a pervasive activity that appears in every engineering project, while design engineering is a specific branch of engineering. Engineering design is also heavily dependent on subjective concepts, such as thinking processes. Although attempts have been made to formalize design engineering as a science, the appearance of various, quite disparate, schools of thought indicates that design engineering is an activity in evolution, whereby research is still needed to lay its foundations in a broadly acceptable framework.

## 3.2 The Engineer: A Professional

The Canadian Council of Professional Engineers (CCPE) is a national organization of provincial associations[1] that, inter alia, issues licences, and **more importantly, ensures the quality of the profession in Canada**. In 1965, the CCPE created the Canadian Engineering Accreditation Board (CEAB), a permanent body whose role (CEAB, 2002) is the accreditation of undergraduate engineering programs that provide graduates with the **skills necessary**[2] for registration as a **professional engineer in Canada**. What is the engineering profession? Who is a professional? We will attempt to define the concept of profession in this section and deal with competency in the section below.

### 3.2.1 A Basic Definition of a "Profession"

Over the last 60 years, a significant amount of research, carried out primarily by sociologists studying work groups, has shed light on the concept of professionalization[3]. Research on this topic has led to the development of various models of profession. More importantly, however, research has brought about a set of characteristics generally shared by all professions, including[4] (Pemberton and Pendergraft, 1998):

- A profession is undergirded by an organized body of **specific knowledge**, which includes theoretical principles as well as **specific, practical skills**. This specialized knowledge serves as one source of legitimization for the profession.
- A profession demands a period of education and training with durations clearly defined by the profession itself. Increasingly, this educational experience takes place in a university environment and at a post-baccalaureate level. The training includes abstract and **theoretical knowledge as well as the more technical skills of the field**.

[1] Ordre des ingénieurs du Québec-(OIQ), Professional Engineers Ontario-(PEO), Association of Professional Engineers and Geoscientists of British Columbia-(APEGBC), etc.

[2] While Section 3.4 of the CCPE document entitled "2002 *Accreditation Criteria* and *Procedures*" refers to knowledge, the authors of this document feel that the issue at stake is skills, since knowledge comprises only a portion of the resources needed to develop skills

[3] Professionalization is the process through which a trade acquires the characteristics of a profession (creation of a new profession). For example, the creation of the CCPE in 1936 led to the professionalization of engineering

[4] Pemberton and Pendergraft present eight characteristics shared by a number of recognized professions

- Community endorsement of a profession becomes strong enough over time so that the profession achieves the autonomy **to set its own educational standards, curriculum accreditation, and a legally sanctioned licensing or certification system.** This licensing system has the force of law in that no one can practice the trade without proper credentials.

These few characteristics clearly illustrate that a profession is built on a body of knowledge (for example, engineering sciences) as well as skills of a practical and specific nature.

### 3.2.2 A Definition of the Engineering Profession

In their book on engineers and their profession, Kemper and Sanders (2001) offer a definition of the profession

> *A calling requiring specialized knowledge and often long and intensive preparation including instructions in skills and methods as well as in the scientific, historical, or scholarly principles underlying such skills and methods, maintaining by force of organization and concerted opinion high standards of achievement and conduct, and committing its members to continued study and to a kind of work which has its prime purpose the rendering of a public service.*

In its guide on the professional practice of engineering in Canada (CCPE, 2001b), the Canadian Council of Professional Engineers (CCPE) defines the characteristics of the profession of engineering as:

> *A profession is a learned calling that requires advanced* ***knowledge, understanding, and abilities*** *gained from intensive and specialized education, training, and practical experience. Members of a profession limit their activities to their areas of knowledge and experience, doing so out of commitment to serve and protect the public. Professional practitioners also ensure that* ***their competency*** *is maintained throughout their careers.*

Again, an important feature of the foregoing definitions is that a profession is based on the acquisition of a body of specialized knowledge **as well as the mastery of a set of skills and methods (know-how)**.

### 3.2.3 A Holistic Definition of a "Professional"

Over the last 20 years or so, a significant amount of research, including that of Schön (Harris, 1993), have taken a critical look at the epistemology of professional practice. According to Schön, professional practice is not founded solely on theoretical, technical and practical knowledge, but also on a set of skills:

> *In addition to theoretical and technical knowledge, effective professional practice requires* ***reflective***[5] ***and practical knowledge and competencies*** *for dealing with problems in the indeterminate zones of practice, that is, the areas that do not yield to technical or familiar solutions.* ***These competencies are critically important to the education and development of professionals*** *in the climate of rapid technological, cultural and economic change* (Harris, 1993).

[5] Knowing-in-action, learned through experience, reflection-in-action, and reflection-about-action

A number of other researchers in the field of professionalization and skills, such as Le Boterf (2002), share this broadened vision of the profession. Table 3.1 summarizes Le Boterf's definition of a professional.

| | | |
|---|---|---|
| The professional has the ability to manage a set of professional situations. The ability... | to act and to react with relevance | to do what is necessary |
| | | to look further than the prescribed solutions |
| | | to make critical choices |
| | | to arbitrate, to negotiate, to decide |
| | | to do a series of actions according to a purpose |
| | to combine various resources and to harness them in a given context | to build competencies from various resources |
| | | to take advantage not only of her or his own resources (knowledge, know-how, etc.) but also the ones in her or his environment. |
| | to re-apply or to re-target | to memorize multiple solutions and typical solutions |
| | | to see the big picture |
| | | to use meta-knowledge for modelling |
| | | to identify and to interpret various indicators in a context |
| | to learn and learn how to learn | to draw lessons from experience; to transform her or his actions into experiences |
| | | to describe how to learn |
| | to engage oneself | to be subjective |
| | | To take risks |
| | | to undertake |
| | | to make professional and ethical decisions |

Table 3.1: Definition of a Professional (Le Boterf, 2002)

Le Boterf's definition clearly demonstrates that, while professional practice is based on skills developed using the individual's inventory of resources (e.g. knowledge, know-how, aptitudes, etc.), it also involves her or his environment (construction of collective skills).

Lastly, the observation is the same if we refer back to the CCPE (2001b) definition of professional engineering practice:

> *The "practice of professional engineering" means* ***any act of planning, designing, composing, evaluating, advising, reporting, directing or supervising, or managing*** *any of the foregoing, that requires the application of engineering principles and that concerns the safeguarding of life, health, property, economic interests, the public welfare or the environment.*

We feel that it is impossible to plan, design, evaluate, supervise, manage, document and so on **without developing the necessary skills, either wholly or partially, during the engineer's academic training**.

## 3.3 Competency

Previously, we indicated that professional practice is not founded solely on theoretical, technical and practical knowledge, but also on a set of skills. On the other hand, this raises a question: what is competency?

The *Grand dictionnaire terminologique* (Office québécois de la langue française, 2004) defines competency as:

> *A body of knowledge, know-how and personality traits required for performing adequately specific tasks or succeeding in the exercise of an occupation.*

This general definition has two important features. First of all, competency is based on a set of knowledge, know-how, and personality traits. Secondly, competency is not measured with respect to acquired knowledge alone, but rather by a person's capacity to carry out activities in a specific professional practice context. In a reflection on engineering of professional and technical training, Quebec's Department of Education (MEQ) offered a similar observation in defining the basic characteristics of competency (MEQ, 2002), some of whose fundamental characteristics are:

- Competency is always defined **as the capacity of an individual to do something**, rather than to demonstrate her or his knowledge;
- Competency is inseparable from **the context of practice in real situations**;
- Competency should be seen as the result of a learning process integrating various resources (knowledge, know-how, aptitudes, etc.).

In his book on engineering skills, Le Boterf (2000) touches on the question of the resources needed to build competency, insisting in that competency can only be measured in connection with performing an activity.

> "*Competency is a construction of resources. It is the result of a combination of many resources such as knowledge (structured set of knowledge), know-how (methods and tools necessary for the success of an activity), and aptitudes (behaviours).* ***Competency can only be measured within an activity.***"

It is now clear that competency is built from resources and can only be measured[6] in the context of professional practice. On the other hand, the issue of resources needed to build skills remains relatively open.Le Boterf (2000) recently proposed a classification and description of the resources that an individual needs in order to build the skills of a professional, as summarized in Table 3.2.

[6] The development of competencies during university training requires in-context educational activities and opportunities (e.g. design projects) that allow the student to demonstrate her or his ability to perform normal activities involved in the professional practice

In summary, engineering competency is about building on a set of resources such as knowledge, know-how, and personality traits that equip the engineer to manage all situations of professional practice including **designing products, systems and processes**. In Chapter 4, we include the results of a literature survey on engineering design competency.

| **Type** | | **Description** |
|---|---|---|
| Knowledge | General knowledge | To understand a phenomenon, a situation, a problem, a process, etc. |
| | Specific knowledge in a professional environment | To know the technologies, the rules, the standards, the culture, etc. |
| | Knowledge of procedures | To know the procedures, the methods, the processes, etc. |
| Skills | Procedural skills | To know how to use methods, procedures, technologies, etc. |
| | Experiential skills | To know how to use empirical knowledge (e.g. rules of thumb) |
| | Social skills | To know how to listen, to cooperate, to work in a team, etc. |
| | Cognitive skills | To solve problems, to design, to manage a project, to make decisions, etc. |
| Personality traits | | Initiative, thorough, curious, etc. |
| Other resources (e.g. emotional intelligence) | | To manage one's (personal and professional) life, to feel (intuition, perception, etc.) |

Table 3.2: Resources for building competencies

# Chapter 4

# Engineering Design Competency: A Literature Review

## 4.1 A Competent Design Engineer

We are interested in establishing a profile of knowledge, skills, personality traits and behaviours that define a competent design engineer.

A review of both the scholarly and the industry-oriented literature offers a rich description of professional engineering competencies in general. But what does it say about the design engineer? Is there a definitive list of characteristics that sets design engineers apart from other engineering practitioners?

North American educators typically approach design as a subset of skills for all engineers, but based on industrial demand (Frise *et al.*, 2002); there are too few institutions that explicitly train engineers for design competency.

Academe and industry are increasingly collaborating to establish a baseline for engineering design competency among engineering undergraduates. Examples include a broader outcome-oriented assessment under the ABET EC-2000 regimes (Bell, 2000; DeLyser and Hamstad, 2000; McCowan and Knapper, 2002) as well as design-oriented industry/academic initiatives like TIDEE[1] (Davis *et al.*, 1996) and CDIO[2] (Crawley, 2002).

Apart from recent North American efforts to bolster engineering design competency, there is a fair amount of literature outlining the development of established European design engineering programs (Buijs and Valkenburg, 2003), industry surveys on design skills (Frise *et al.*, 2002; Eggert, 2002; Frise *et al.*, 2003), industry literature on engineering competency (Leiper and Khan, 1999; Wisler, 2003) and pre-existing design engineering literature (Hubka and Eder, 1992). These offer further clues to the "profile" of the design engineering competency.

The North American literature does not provide a comprehensive and prescriptive definition of the engineer's competency as a designer, or an explicit list of educational outcomes specific to the practice of engineering design.

Recent papers that identify design as an engineering discipline in its own right place design engineers at the interface (Buijs and Valkenburg, 2003; Frise *et al.*, 2003) of science, analysis (Sheppard, 1999; Evatt, 2001), art (Eder, 1995) and business (Buijs and Valkenburg, 2003; Frise

[1] Transferable Integrated Design Engineering Education.
[2] Conceiving, Designing, Implementing and Operating real-world systems and products

*et al.*, 2003).

Many engineering educators believe that students should understand how to generate design specifications and how to proceed from design specifications to a final product by establishing objectives and criteria, generating alternatives, synthesizing, analyzing, constructing, testing and evaluating (Sheppard, 1999).

## 4.2 Established Skills for Design Engineers

With the previous discussion on a competent design engineer, the search for skills and attributes of accomplished design engineers can begin. A brief survey of papers and articles over the last eight years offers a number of hints as to the intellectual, professional and personality profile of a competent design engineer.

This review first examines skills that set design engineers apart from other practitioners. It reviews other attributes that are sought in design engineers, including experience, personality traits, business skills, communications skills, teamwork and "other" technical skills.

### 4.2.1 Specific Design-Process Activities

Industry and academe cite a wide range of preferences in formal design methodologies. While each industry segment has its favourite design methods, it typically seeks engineers able to implement:

- Methods and rules for the larger design process including: Design for X (Oakley, 1990; Boothroyd *et al.*, 1994; Fu *et al.*, 2000; Boothroyd, 2001; Bajaj *et al.*, 2002; Eggert, 2002; Frise *et al.*, 2002; Gattiker, 2003); identification of constraints and needs (e.g. QFD) (Radcliffe and Harrison, 1994; Eggert, 2002); quality control processes (e.g. Six Sigma, TQM) (Eggert, 2002; Frise *et al.*, 2002); and use of project management structures (Dekker, 1996; Evbuomwan *et al.*, 1996; Asbornjen and Hamann, 2000; Boothroyd, 2001; Eggert, 2002; Frise *et al.*, 2002; McCowan and Knapper, 2002);

- rules for design analysis and design improvement, e.g. Failure Mode Effect Analysis, product testing, process integration, etc. (Boothroyd *et al.*, 1994; Zhang, 1998; Eggert, 2002; Lewin *et al.*, 2002);

- methods for creativity-enhancement, e.g. brainstorming and TRIZ (Ertas and Jones, 1996; Dieter, 2000; Frise *et al.*, 2002; Eggert, 2002; TRIZ, 2004);

- specific technical skills with special emphasis in design, including: solid modelling techniques (Frise *et al.*, 2002); computer-aided design (CAD) (Davis *et al.*, 1996; Sorby *et al.*, 2000; Evatt, 2001; Eggert, 2002; Lewin *et al.*, 2002); geometric dimensioning and tolerancing (GD&T) (Frise *et al.*, 2002); computer-assisted design (CAD) (Davis *et al.*, 1996; Eggert, 2002); and computational fluid dynamics (CFD) (Kundu and Raghunathan, 2000; Birtigh *et al.*, 2000); and

- other design knowledge, including safety methodologies (McCowan and Knapper, 2002; Eggert, 2002; Hales, 2003; Guzman and Vudgdelija, 2003; Kelly, 2004), regulatory issues (Eggert, 2002) and human factors (Eggert, 2002; Toft *et al.*, 2003b,a).

### 4.2.2 Experience and "Know-how"

Above all other skill-level considerations, design engineers require some level of hands-on competency in the use of machines, tools or processes relevant to their field (Hubka and Eder, 1992; Bell, 2000; Evatt, 2001; CCPE, 2001a; Frise *et al.*, 2002; Eggert, 2002; Frise *et al.*, 2003). These skills are insufficient among North American engineering graduates, based on the frequency with which this issue appears in the literature.

A recurring theme on the issue of experience is the need for more practice in the educational process. Organizations like ABET have mandated outcome-based measures of undergraduate competencies with implicit consequences for proven experiential learning (Davis *et al.*, 1996; Trevisan *et al.*, 1998; Bell, 2000; DeLyser and Hamstad, 2000; McCowan and Knapper, 2002).

Where design engineering skills have been identified as separate from typical engineering science, there is a recurring principle of learning-by-doing (Hubka and Eder, 1992). Experiential competency is defined as an innate ability and as a "set of instincts about the likely consequences of certain choices which every professional faces every day." (Frise *et al.*, 2003).

### 4.2.3 Attitudes Toward Design Engineering

Professional attitude is widely cited as a key competency for engineers in general (Frise *et al.*, 2002; Eggert, 2002; Wisler, 2003), along with the ability to adapt to changes in circumstances (Frise *et al.*, 2002; Wisler, 2003).

Design engineering practice suffers from varying attitudinal pathologies. "Not-invented-here" attitudes (Wisler, 2003), confusion of originality with creativity (Thomas and Ame, 2003), notions of design as an individual activity (Thomas and Ame, 2003), and an unwillingness to leverage the knowledge of technicians or tradesmen (Eggert, 2002) are recurring problems among new graduates of university engineering programs.

### 4.2.4 Business Skills

The recent literature suggests that novice engineers require at least an introductory familiarity with business issues. These skills are identified as pertinent to all engineers - not just design engineers. However, customer awareness is emphasized in the design context (Hearne, 1998; Leiper and Khan, 1999; Wisler, 2003).

Important business issues for engineers include: project management skills (Lahidji, 2000; CCPE, 2001a; Eggert, 2002; Lauche, 2003); customer awareness; knowledge of basic issues in business finance (cost of money, corporate ownership structures and liabilities) (CCPE, 2001a; McCowan and Knapper, 2002; Eggert, 2002; Wisler, 2003); basic economic principles (Lahidji, 2000); an appreciation for the nature of interdisciplinary engineering problems (Wisler, 2003); the ability to evaluate product development costs (Bell, 2000); risk analysis and budgeting (Frise *et al.*, 2002); social skills applicable to a multicultural business environment (Lahidji, 2000; Wisler, 2003); an understanding of corporate culture and the global nature of business (Dempster *et al.*, 2001; Sekiguchi *et al.*, 2001; Frise *et al.*, 2002; Wisler, 2003); an appreciation for intellectual property (Wisler, 2003); professional attitudes (CCPE, 2001a; Eggert, 2002; Wisler, 2003); salesmanship (presentation skills) (Eggert, 2002; Wisler, 2003); and an ability to assess the workplace performance of oneself and of others (Wisler, 2003).

### 4.2.5 Communications Skills

Communications skills were persistently at, or near, the top of design competency requirements in industry and academe. Employers expect young engineers to be fluent in the use of engineering drawings (Davis *et al.*, 1996; Eggert, 2002; Frise *et al.*, 2002), to be able to draft comprehensible, compelling reports (Eggert, 2002), to express themselves orally (Davis *et al.*, 1996; Eggert, 2002; Frise *et al.*, 2002), listen effectively (Davis *et al.*, 1996), and to be able to "sell" concepts, products and themselves (Eggert, 2002; Wisler, 2003) to the technically savvy as well as to the layman (Davis *et al.*, 1996).

### 4.2.6 Teamwork Skills

Every comprehensive list of engineering competencies includes the ability to work effectively in teams. Typically, teamwork skills receive the highest priority among design engineering competencies (Frise *et al.*, 2002; Eggert, 2002). Yet, despite the importance of teamwork and other social skills, they are not assessed systematically in the process of educating design engineers (Cowdroy and Williams, 2002; Lauche, 2003).

Design engineers must be able to form teams, and work with a multicultural workforce (Lahidji, 2000; Wisler, 2003) in an interdisciplinary environment (Davis *et al.*, 1996; Wisler, 2003). Engineers must also be skilled in conflict management (Frise *et al.*, 2002).

KarenLauche (2003), of the University of Aberdeen, has identified several important communications and project management skills (Frankenberger and Badke-Schaub, 1998; Lauche *et al.*, 2001; Cowdroy and Williams, 2002) for the design process, including: negotiation with clients; problem-solving; acceptance of responsibility; interpersonal skills; planning; exchanging information; coordinating activities; assessing capabilities of others; workload management; team building and collaboration.

### 4.2.7 Technical Skills

There is little apparent concern over the level of competency for design engineers in mathematics, basic sciences and engineering sciences (CCPE, 2001a; Eggert, 2002; Frise *et al.*, 2003)— although graduates may have trouble applying those skills to proper technical design analysis (Dempster *et al.*, 2001).

The University of Windsor's "Product Engineering Process" survey on mechanical engineering skills in general includes analysis and testing skills (FEA, DOE, mechatronics and control, process improvement tools, statistical process control, physical testing processes) and several specific manufacturing skills (Frise *et al.*, 2002). Areas identified for improvement among Canadian engineers include geometric dimensioning and tolerancing, precision measurement, and shop-floor skills.

As previously mentioned, technical skills related to interpreting and creating engineering drawings are critically important. There is, however, some variation on the perceived necessity for novice engineers to have substantial expertise with specific CAD/CAM packages (Davis *et al.*, 1996; Evatt, 2001; Eggert, 2002). Some prospective employers view fluency as a key skill; others are only concerned with the graduates' understanding of the underlying fundamentals on which CAD/CAM is built (Eggert, 2002).

Codes and standards are mentioned in industry surveys (CCPE, 2001a; Eggert, 2002; Frise *et al.*, 2002)—insofar as novice engineers should be familiar with product standards (e.g. ANSI, CSA, UL), testing standards (e.g. ASTM), process standards (e.g. ISO) and standards of professional conduct (e.g. PEO Code of Conduct).

## 4.3 Assessment and Evaluation

### 4.3.1 Introduction

There is a necessary relationship between the development of a list of competencies, and the use of that list for three purposes: student assessment; program evaluation; and curriculum design and re-evaluation. If, for example, problem identification is selected as a competency, each individual student or group can be assessed for a level of achievement in that competency. A program can be evaluated on that competency for accreditation purposes or internally for quality improvement by assessing the average level of achievement over all students in the program. Since each competency will be selected as a component of one or more program activities (such as courses or projects), the overall curriculum can be periodically evaluated to monitor whether it contains a suitable level of exposure to allow for the development of that competency in students.

### 4.3.2 Student Assessment

The definition and assessment of a limited number of student competencies in student reports and design projects is relatively common in engineering programs. Such assessments often take the form of rubrics — rules for scoring the quality of a student's work under specific categories, with explicit evaluation levels defined for each category. For example, rubrics are frequently used in the assessment of students' written communication skills. Employing design qualities as categories, Thompson (2001) further generalized the use of rubrics in the context of assessing engineering student design projects to permit students to trade off several different approaches to design (e.g. an innovative but high-risk approach versus a conservative but low-risk method).

More extensive definitions and measurement of competencies have also been used in breaking down design projects into discrete project steps or phases. Davis *et al.* (1996) identified the relative importance (e.g. primary, secondary) of eight competencies to the 10 phases of a proposed project. This information was initially proposed to assist in the project-selection process. By attaching a defined level of achievement to each competency, Davis *et al.* (1997) later proposed that these levels form the basis for the assessment of students through several means (examination, discussion, observation and product assessment).

For certain competencies in team performance, peer evaluations have been used as a part of the student evaluation process. Byrd and Hudgins describe a senior design course project in which this formed 10% of a student's mark (Byrd and Hudgins, 1995).

At Sherbrooke University, logbook and peer evaluations are used in students' major design projects. The logbook is used to evaluate the work done by each team member, while peer evaluations are used to weight the overall contribution of each member to the team effort.

### 4.3.3 Program Evaluation

The professional engineering association in the United Kingdom defines a list of accreditation topics (e.g. knowledge, design, analysis) with no expected level of achievement. The programs in each institution are evaluated by accreditation organizations in the various branches of engineering. In the United States, ABET has compiled a list of outcomes of student training. These outcomes are not all linked to a level of achievement in a specific task and, hence, require interpretation by each institution. For example, the ABET outcome "An ability to function on teams" does not provide a level of expected proficiency, either in the overall activity or in the subtasks.

Program evaluation at Aalborg University, well known for its "project organized" education system, has been internally carried out by means of student surveys (QDGEES, 1992). The student survey, along with a survey of graduates of the program, formed a part of the background for a 1992 international review of Electrical Engineering Education at Aalborg University. One of the approaches taken in the survey was to evaluate the perceived level and the desired level of the program's concentration on contrasting activities (e.g. theory vs. practice, individual vs. group work). A second evaluation approach taken was to ask the students to suggest a level (more, less, adequate) of desired content in various course categories (e.g. physics, engineering science, economics) compared to the present level.

### 4.3.4 Curriculum Design and Evaluation

A comprehensive effort to define a set of competencies arose from the work of Crawley (2001) to define a "CDIO Syllabus." In this work, a list of 13 goals at CDIO level-2 (with elements such as teamwork) was selected and compared with a number of educational goals or requirements (e.g. ABET, Boeing, MIT). A list of five specific assessment levels, ranging from "to have experienced or been exposed to" to "to be able to lead or innovate in" was, then, created. The list of goals was sent out to a number of stake-holders (alumni, employers, etc.), who were asked to rank each goal against the five assessment levels in order to obtain an expected average level of achievement in each competency.

The list was then expanded to 67 CDIO level-3 attributes (for example teamwork contained "forming effective teams", "team operation", etc.). The stake-holders were asked to rank the relative importance of each level-3 competency relative to the previously-assessed average level of competency at level-2.

A further expanded CDIO level-3 list was then constructed, containing sentences that represented the expected level of achievement, based on Bloom's taxonomy of learning (Bloom, 1956). These sentences formed a more detailed list of 276 competency attributes. Examples include: "evaluate supporting evidence", in which the verb 'to evaluate' is classified by Bloom as requiring a high level proficiency, and, "recognize partnerships and alliances", in which the verb 'to recognize' indicates a requirement for low-level competency attributes. Proposed for the intended task of curriculum definition, this extensive level-3 list of possible competencies appears to be very long for either student assessment purposes or for program review by stake-holders. Even for the purpose of curriculum definition, the list was reduced by Malmqvist *et al.* (2002) to 25 of the 67 level-3 attributes in Crawley's work.

### 4.3.5 Discussion

The purpose of the assessment and the tool itself will determine the detail of the list of competencies and the corresponding comprehensiveness of the competency definitions. For example, if employers are to be asked to complete a survey about the effectiveness of a particular program in training graduates hired in the last five years, it is not practical to request that they evaluate an extensive list of competencies. An expanded list of competencies may, however, be useful to design or redesign a program.

# Chapter 5

# Engineering Design Competency: A Proposal

A proposed design competency model is offered in this chapter. As indicated in the introduction, the model is intended to provide inspiration for engineering schools and to act as a resource in the continued advancement in engineering design education. The proposed model should be considered as Version 1, with the expectation that it will evolve and that greater depth will develop over time[1].

## 5.1 Engineering Design Competency for all Engineering Disciplines

Table 5.1 provides a summary of the proposed definition of engineering design competency as applicable to all disciplines. The list is followed by an explanation, expansion and examples of competency areas specifically related to engineering design. Suitable references and links to resources in each of the competency areas have been provided, where possible. Expansion of the competencies as related to general knowledge is not provided.

The list is consistent with the objectives stated in the introduction, that is, a list from which an institution and program may draw inspiration. It is not expected that a single graduate or an engineering program would be competent in all of the listed items. It is hoped that the listing and the supporting descriptive material will provide guidance in curriculum development and assist in strengthening the breadth of competencies that are strived for by students, programs and institutions.

An individual engineering discipline may opt to build on this work to provide specific dimensions that are appropriate for that discipline. We leave this task either to the future or to others.

[1] The number of lines provided in this version should not be interpreted as an indication of the relative importance of an item

| Type | Description | Engineering - All Disciplines | |
|---|---|---|---|
| General knowledge | To understand a phenomenon, a situation, a problem, a process, etc | Mathematics | Linear Algebra, Calculus, Differential Equations, Probability, Statistics, Numerical Methods, Partial Differential Equations, etc. |
| | | Basic Sciences | Chemistry, Physics, Biology, Earth Science, etc. |
| | | Engineering Sciences | Mechanics, Materials, Fluid Mechanics, Circuits, Thermodynamics, Heat Transfer, Mass Transfer, Automation, etc. |
| Specific knowledge in a professional environment | To know the technologies, the rules, the standards, the culture, etc. | Technologies, standards, regulations, safety, liability, intellectual property, ethics, role in the society | |
| Knowledge of procedures | To know the procedures, the methods, the processes, etc | Product development process, engineering design process, engineering design tools (market research, functional analysis, QFD, Pugh (1996), FMEA, CAD, CAE, design for cost and cost estimation, etc.) | |
| Operational skills | To know how to use methods, procedures, technologies, etc. | To have executed and practiced the design process | |
| Experiential skills | To know how to use tacit knowledge | Design by similarity, design by experience, etc. | |
| Social/personal skills | To know how to listen, to cooperate, to work in a team, etc | Teamwork, communications, leadership, negotiation, professionalism | |
| | Initiative, thorough, curious, etc. | Teamwork, communications, leadership, negotiation, professionalism | |
| | To manage one's own life (personal and professional), to feel (intuition, perception, etc.) | Teamwork, communications, leadership, negotiation, professionalism | |
| Cognitive skills | To solve problems, to design, to manage a project, to make decision, etc. | To know one's limitations, to create, to look at the big picture, to manage projects (including the systems engineering perspective), to learn how to learn, to manage information and knowledge, to define a problem, to define potential solutions, to learn from past experience, to manage resources, to take risks (risk-management) | |

Table 5.1: Proposed Definition of the Design Engineering Competency

### 5.1.1 Specific Knowledge in a Professional Environment

This section provides perspectives on design competency as related to the broad context of engineering practice. It is essential that a competent design engineer recognize the engineer's role in society and the 'rules' that have been established to help in the performance of this role.

- **Role in Society**

  In the words of the Canadian Council of Professional Engineers (CCPE, 1997):

  > "*Canadian engineers provide leadership to advance the quality of life through the creative, responsible and progressive application of engineering principles in the global context.*"

  "Quality of life" is a broad term that recognizes the importance of economic, social and environmental domains that are all essential for realizing a high standard of living. These domains are the pillars of sustainable development (Commission on Environment and Development, 1987). CEAB accreditation guidelines stress that knowledge of the principles of sustainable development is essential for all engineers (CEAB, 2002).

- **Safety**

  The practice of engineering is fundamentally about the protection of public safety. As designers, graduating engineers should have been exposed to and had some experience with one or more of the classical techniques to identify and reduce safety risks. Hazard and Operability Studies (HAZOPS), Failure Mode and Effect Analysis (FMEA) and Failure Trend Analysis (FTA) are three common techniques.

- **Ethics**

  Morrison and Hughes (2003) provide a leading reference on the ethical aspects of Canadian engineering practice.
  Some schools have introduced a code of conduct for their undergraduate students as a means to introduce and integrate ethical considerations into their undergraduate engineering activities.

- **Liability**

  Understanding how to design so that your employer, your client, and the general public are protected adequately is a necessity that follows from the fundamental responsibility for sensible public safety shared by all professional engineers. The need to consider liability arises because engineers choose the degree of safety appropriate for each product or service, and if inappropriate, then the recourse of the affected individual is likely to be litigation.
  Obviously, increased knowledge of the risks and the development of safety features come at a price; engineers must thus make decisions about the appropriate balance between costs and safety during the design process. In addition, products that are sold in different environments are subject to different philosophies on protection of the public. For example in Canada, the constitutional mandate for good government is realized in part through codes and standards that are enforced to protect the general public. In contrast, engineering practices in the United States are often the result of product-liability litigation and the associated precedents of large awards made in jury trials. In the global marketplace, engineers must have the

competency to understand the risks associated with their designs so that sensible decisions about safety standards and corporate exposure can be made.

- **Codes, Laws and Regulations**

  Codes, laws and regulations influence all engineering design and often represent minimum standards that must be ensured.

  Under the Canadian Constitution Act, the responsibility for regulating buildings rests with provincial and territorial governments, but is often transferred to municipalities. The National Research Council of Canada has developed model codes that can be adopted directly by each jurisdiction or modified to varying degrees to address local issues (NRC, 2004). Engineers should have competent knowledge of the key codes, laws and regulations that are relevant to their discipline.

  The Workplace Hazardous Materials Information System (WHMIS), established in 1987, has become fully integrated into the Canadian workplace. All graduating engineers should be knowledgeable of WHMIS and its impact on their designs (WHMIS, 2004).

- **Standards**

  > *If there were no standards, we would soon notice. Standards make an enormous contribution to most aspects of our lives—although very often, that contribution is invisible. It is when there is an absence of standards that their importance is brought home. For example, as purchasers or users of products, we soon notice when they turn out to be of poor quality, do not fit, are incompatible with equipment we already have, are unreliable or dangerous. When products meet our expectations, we tend to take this for granted. We are usually unaware of the role played by standards in raising levels of quality, safety, reliability, efficiency and interchangeability—as well as in providing such benefits at an economical cost* (ISO, 2004).

  Engineers rely on standard components to design and build complex systems. They should know where to look to find standard specifications for a bolt or a pipe. They should know to customize only when necessary.

  New designs and products often must meet certain standards and frequently require certification. Engineers should be aware of standards applicable to their work and of testing and certification processes.

  Due to the success of the International Organization for Standardization series in quality management (ISO 9000) and environmental management (ISO 14000), student exposure to these standards within the engineering curriculum is necessary.

  The International Organization for Standardization (ISO, 2004) and the Canadian Standards Association (CSA, 2004) are two important standards organizations for Canadian engineers; however, there are many more. The TriUniversity Group (TUG) of libraries offer a fairly extensive set of Internet links to standards organizations and writing bodies (TUG, 2004).

- **Intellectual Property**

  Design engineers will use existing intellectual property (IP) in the development of solutions and should expect to create new-IP over the course of their career. Competency starts with respect for existing IP and recognition of new-IP protection.

Graduates should be aware of the various forms of intellectual property (patents, trademarks, copyright and industrial designs). There are a number of good Internet sites providing descriptions of the various forms of IP and providing patent search capabilities (CIPO, 2004; European Patent Office, 2004; USPTO, 2004; WIPO, 2004). Most universities have an intellectual property office that can be an important resource in support of the curriculum. The University of Manitoba has a course that uses existing University IP to motivate engineering designs. Final-year business and engineering teams at the University of British Columbia propose, prototype and prepare a business plan for new products based on market and patentability.

- **Technologies**

  All graduating engineers must have awareness and some technical understanding of a broad range of technologies beyond those of their engineering discipline. This breadth of knowledge is necessary to support the development of creative solutions, to understand engineering systems and components, to work in cross-disciplinary teams and, ultimately to lead larger engineering projects.

  Below we provide a suggested list of technologies that are relevant for all engineers:

  1. Resistors, capacitors, transistors, diodes
  2. Motors
  3. Engines
  4. Heat exchangers
  5. Refrigeration
  6. Electrical generation (from coal to solar)
  7. Telecommunications
  8. Thermostats
  9. Bridges
  10. Sewers
  11. Catalytic converters (as an example of common chemical processes)
  12. Breweries (as an example of common biological processes)

  The above list is composed of: key technologies from various engineering discipline; technologies that are part of everyday society; and technologies that are part of every engineer's role in safety and sustainable development. Obviously, this list is not exhaustive.

### 5.1.2 Knowledge of Procedures

Competency must start with knowledge of procedures, but knowledge itself is not sufficient for a competent design engineer. Knowledge of the design process and various design tools is just the starting point.

- **Design Process**

The design process is described in varying detail by numerous references. Textbooks for engineering design education include (Ertas and Jones, 1996; Dieter, 2000; Ullman, 1997; Voland, 2004), among others.

In the final analysis, knowledge of the design process encompasses the transition from an idea, a vision or a problem to technical specifications of the product, process or solution. Implementation is the conclusive step in the design process. In the words of Petroski (1992), "Design is getting from here to there".

Knowledge includes where R&D, testing, prototypes and pilot scale activities can potentially fit into the process. Knowledge encompasses recognition that the process is most often iterative.

An important element of knowledge competency is being well versed in the terminology associated with the design process. Conceptual design, feasibility study, preliminary design, final design, detailed design, concurrent design and embodiment design are all terms that are used to describe portions of the design process.

- **Design Tools**

  Design tools that support the design process come in many forms, depending on the stage of the process and the nature of the design problem. Tools include people as resources for problem definition and data gathering. Libraries (a term encompassing all information sources) are primary tools in the early information-gathering stage. Knowledge must include awareness of the various types of sources (textbooks, archival literature[2], patents, gray literature, web sites, standards, codes, regulations and people) and the recognition that all sources are important.

  Engineering drawings are essential design tools. Sketches, generated by pencil and paper, are the most frequent beginning in the design process. As a design matures, sophisticated CAE software becomes integral to the process. Knowledge means that the engineer is aware of the role of engineering drawing.

  Engineering calculations are also key design tools, from approximations written on the back of an envelope to sophisticated CAE software, which captures the 3D and transient complexity of a system. Knowledge means that the engineer is aware of the existence and capabilities of these tools.

- **Performance Assessment Against Criteria and Constraints**

  Problem definition usually identifies appropriate constraints (the musts) and desired criteria (the wishes). The constraints must each be achieved. The criteria are dealt with in a collective balancing act. Quantifying each of the identified factors eases the subsequent decision-making stage.

  Cost is always a factor in engineering design, with its estimation becoming an important field of its own. Cost estimation is necessary at various stages of the design process, relying on experience and depending on empirical relations. The chemical engineering field has well developed empirical relations to support cost-estimating (Peters and Timmerhaus, 1991). The Society of Automotive Engineers (SAE) provides a structured format on cost estimation for the student Formula SAE competition (Bowman and Farr, 2000). This format could be effectively used within an engineering curriculum.

  Safety is also an important factor in all designs. HAZOP, FMEA, FTA and risk analysis

[2] Research journals.

can all be used to assess the safety of a given design. Comparison with existing codes and standards is also an important step.

Environmental performance is another common factor. Life cycle analysis, a series of methods for environment assessment of designs that is growing in importance, should be an element in all engineers' knowledge base. Comparison of a design to existing codes and regulations is an integral part of a design environmental assessment.

The literature on engineering design and its practice has introduced the terms: "Design for Cost", "Design for Reliability", "Design for the Environment", and others (Corbett, 1991; Dhillon, 1999; Poli, 2001; Rouse, 1991; NRC, 2004; USEPA, 2004). Increasingly, these terms are collectively referred to as "Design for X"—see DFX terminology (Migliore, 2004). The introduction of these concepts represents an effort to focus design attention on one particular criterion. They imply that design attention for X has been lacking. The fact that there are so many Xs reflects the design challenge of simultaneously optimizing numerous criteria.

- **Decision-Making**

  Decisions are an integral part of the design process. Many formal decisions and many more informal ones are made throughout the process.

  Formal decisions often occur at the conclusion of the conceptual, preliminary and final design stages, as part of recommending the next step and seeking budgetary approval to proceed to the next stage. Procedures have been developed to formalize this decision-making process as part of fostering objectivity. Objectivity is important in all settings, but it is particularly important in the public sector. The decision-matrix method is one common formalized approach that is relatively simple to execute (Ullman, 1997). However, it is important for students and engineers to recognize that subjectivity quickly becomes a part of the decision-matrix approach through the selection of criteria weightings and scoring rules. Informal decisions are made almost continuously in the design process. Everything from assumptions made in a detailed calculation to what options to pursue following a brainstorming exercise involves decision-making. The challenge is to make these choices consciously and as objectively as possible without getting bogged down in analysis, as **too much analysis leads to paralysis**.

  Decision-making by consensus is an important skill for effective teams (Levi, 2001): "It takes time, energy and skill to reach consensus but consensus decisions have a greater likelihood of being implemented by the team".

### 5.1.3 Operational Skills

Operational skills are critical to achieving and demonstrating competency. These skills pertain to the ability to do something; in engineering design terms, operational skills pertain to the ability to do something in a real setting. The knowledge of procedures can be delivered in a lecture and assessed on an exam. Operational skills cover all of the same topics and domains, but must be experienced in design projects and can only be assessed in practice.

Throughout the engineering curriculum, students need an opportunity to engage in the design process, use the design tools, evaluate their ideas, make decisions and, ultimately, validate their work through implementation.

Many engineering schools place this experience in the latter part of the curriculum; some disperse it throughout the curriculum; and, some even have an established sequence of design courses. Each of these approaches divides the process into smaller, manageable, single course bits.

Mechanical Engineering at the University of Sherbrooke (Charron *et al.*, 2002) has a unique multi-course sequence that delivers the experience in a single integrated package. The students start at problem definition and carry it all the way through to implementation.

### 5.1.4 Experiential Skills

Engineering design draws on experience. The collective experience of engineers is captured in standards and codes, laws and regulations, textbooks and, increasingly, highly specialized software, e.g. code for CFD, FEA, computer algebra, scientific numeric calculations, simulation, optimization, to name just a few. Experience is also captured in the products of engineering design that everyone uses everyday, e.g. toaster, telephone, toilet, car and computer, and the engineered products that are in the background of our lives, e.g. electrical generating station, wastewater treatment plant, and the embedded chip controlling the elevator. Petroski (1992) provides insight into the reliance of engineering design on the experience of failures.

In addition to collective experience, each designer relies on her or his personal experience in the development of her or his designs. This individual experience often comes down to judgment: "Design projects in universities go some way to develop this engineering judgment" (Hager, 1997). Judgment is the ability to consider a list of alternatives and make a decision—whether something can be fabricated, or is easy to use, safe or practical. Corbett (1991) provide guidance in design for manufacture. Rouse (1991) and Toft *et al.* (2003b) provide insights into human factors.

Students need opportunities to design from, and to, codes and standards, to design from established recipes and to make judgments for themselves. They need experience with failure in their designs.

### 5.1.5 Social/Personal Skills

As a result of the complexity of today's systems and the corresponding diversity of expertise required to take an idea to 'market', engineering design relies heavily on people's skills.

- **Teamwork**

  Strong teamwork skills are developed through experience; however, Pohlexperience alone will not automatically make an individual an effective team player. Opportunities for constructive reflection are essential if skills are to progress. Reflection requires an awareness of teamwork fundamentals. Many engineering design texts, e.g., (Dieter, 2000), provide insight into teamwork. Teamwork is not unique to the engineering field, a number of excellent references on effective team building, e.g., (Levi, 2001; West *et al.*, 2003), being available.

  Students should be aware of the classical team-life cycle (Lumsdaine and Lumsdaine, 1995) in order to recognize that the challenges they face within their teams are normal. Students should know the characteristics of good teams and the indicators of a team in trouble (Levi, 2001).

  Learning styles differ from one student to the next. Lumsdaine and Lumsdaine (1995) provide excellent insight in this area, particularly in the context of engineering and engineering education. Students (and faculty) should be made aware of these differences, their potential impact on the dynamics of their design team, and advantages and disadvantages of teams that are composed of individuals with differing learning styles.

Evaluation and rewards are crucial components of teamwork. A balance must be struck between individual- and team-based rewards, fostering a commitment to the team's goals and the team itself while at the same time providing an incentive to the individual and the individual's performance (Levi, 2001). In educational settings, this balance is not easily achieved.

Conflict management is an important dimension of effective team skills. Conflict is a necessary part of the design process; however, not all conflict is good. Students should be aware of the various types and causes of conflict. West *et al.* (2003) provides strategies for effective conflict resolution.

- **Communication Skills**

Traditionally, a blueprint was THE engineering design communication tool. While drawings continue to be a critical aspect of communication in engineering design, a competent design engineer should be knowledgeable of the various common drawing formats and capable of recognizing important conventions and symbols across all engineering disciplines (a resistor, a control valve, a welded joint, etc.). All engineers should have a first-level capacity to read blueprints, process flow diagrams, process and instrumentation drawings, and circuit drawings. Engineers should have a high-level capacity to read drawings relevant to their discipline and an acceptable capacity to create drawings suitable to their discipline using current software (Austin, 1979; Jensen, 1979).

Written communication extends beyond drawings to design reports, technical specifications and design appendices. Many introductory engineering design textbooks provide guidance in technical writing and engineering reports (Dieter, 2000; Andrews *et al.*, 2003; Voland, 2004).

Competency development in written communication relies on practice, quality feedback and the opportunity to rewrite.

Design logbooks (or notebooks) are an essential format for the documentation of an individual's design development and decision-making (Ullman, 1997). Good *et al.* (2001) discuss the pedagogical benefits of using electronic journals as a means to encourage and assess reflective learning. There are a number of examples of logbook use in engineering design courses (Florida Atlantic University, 2004; University of Illinois at Chicago, 2004)

Oral communication takes on many forms in the practice of engineering design. Design reviews, public meetings with formal rules of order, one-on-one exchanges (including interviews), and individual and team presentations. All of these formats can be with and without the use of visual aids. Visual aids can include animate objects, large-format design drawings, posters, overheads and computer projection systems. Competent engineers must have experienced this diversity of communication settings, understand the similarities and differences and be capable of preparing effective presentations and visual aids. Numerous resources are available to provide guidance (Fodor and Roffe-Steinrotter, 1998; Good *et al.*, 2001); however, only experience with feedback will develop competency.

In both written and oral formats, it is necessary to match the communication with the needs of the audience. The capacity to communicate our designs to technical and non-technical clients is an important dimension associated with competent design engineers.

- **Leadership**

  "A leader is someone that can influence an organized group toward accomplishing its goals." (McCarthy and Hatcher, 2002). Open-ended design projects require teamwork, communication and decisions, and are an effective means of embedding leadership education into the curriculum (McCarthy and Hatcher, 2002).

  Leadership is an important skill and comes in many styles (Mello, 1999; Dieter, 2000; SAE, 2004). Some argue that effective leaders have the flexibility to use the appropriate style to fit the context (SAE, 2004). Current western leadership theories point to delegation, empowerment and power-sharing styles; however, this type of leadership is not universally successful (Mello, 1999). Some cultures are more accepting of autocratic leadership (Mello, 1999).

  A team environment often requires a facilitative leader, someone who is able to establish a collegial and open environment, encourage a supportive and cohesive group, motivate and provide guidance, while ensuring progress is being made toward the teams' goals (Dieter, 2000; Voland, 2004). Different leadership styles will influence creativity (Young, 2000).

  Faculty often recognize students who are natural leaders; however, education must go beyond this recognition and help all students to become more effective leaders. Rausch (Mellahi, 2000) offers three guideline questions that all managers should consider in their work. These questions could benefit engineering students in two ways. The questions could help students to consider the problem beyond the technical domain and will help them develop leadership skills. Rausch's questions are:

  - "What else could we do to make sure all our stake-holders will like what we are doing, and none will throw roadblocks in the way, or sit on their hands, wasting time?"
  - "What else do we have to consider to make sure everyone involved, including the suppliers, clients, customers, the public, and yes, even the adversaries, know what they should know, and that they can do what they should do—so less time is wasted in fumbling, on mistakes, and in answering questions?"
  - "What else should we think about, before we go ahead, to make sure that what we are doing will best get us to where we want to go, and not have us waste time zigzagging?"

### 5.1.6 Cognitive Skills

Cognitive skills include the capacity to do projects, solve problems, define creative strategies, take risks (risk management) and to consider economic, business and marketing concerns.

- **Project Management**

  Effective engineering design relies on effective overall project management. Gantt charts and the critical path method (CPM) are often used in the support of design project planning and scheduling (Ertas and Jones, 1996; Andrews *et al.*, 2003).

- **Problem-Solving**

  Effective problem-solving uses both creative and critical thinking[3]. Divergent and convergent thinking approaches (Isaksen *et al.*, 1994) complement each other.

[3] Critical thinking has to do with analyzing, evaluating and developing options

- **Creative Strategies**

  A creative engineering solution must be unique and must solve the problem. "Beam me up, Scotty!" is certainly a creative idea to our transportation challenges; but it is not, at least in the foreseeable future, a workable engineering solution.

  Brainstorming is commonly introduced in the engineering design curriculum and included in many introductory engineering design texts (Ertas and Jones, 1996; Dieter, 2000). Numerous techniques have been developed to overcome mental blocks such as SCAMPER (substitute, combine, adapt, modify, put to another use, eliminate, reverse), the use of analogies, a.k.a. synectics (Gordon, 1960), and the use of random inputs (Dieter, 2000). TRIZ (Theory on Inventive Problem Solving) may be an effective means of triggering creative solutions to common engineering design conflicts (Dieter, 2000; TRIZ, 2004).

  Creativity must be practiced. This is recognized in the arts and architecture but is often lost in engineering. Black's creativity challenges (Black, 2002) have many quick strategies that can be used in an engineering design context.

  Creativity depends on a supportive environment—fear of failure is a major deterrent to creativity. Engineering schools need to look to arts, architecture and other departments to develop course and grading approaches that genuinely foster creativity.

- **Risk-Management**

  The purpose of risk-management (Wideman, 1992) is to:

  - Specifically identify factors that are likely to impact the objectives of a project with regard to scope, quality, time and cost;
  - Quantify the likely impact of each factor;
  - Give a baseline for project noncontrollables;
  - Mitigate impacts by exercising influence over project controllables.

- **Economics, Business and Marketing**

  The ability to design a product or process does not necessarily ensure a successful result. In virtually all engineering projects, the solution must be affordable to the client. A 19th-century civil engineer, Arthur M. Wellington, is credited with one definition of engineering being "the art of doing that well with one dollar which any bungler can do with two" (Rausch, 1999). Hence, engineering design competency is not complete without a fundamental understanding of engineering economics. Design decisions are heavily influenced by economic factors such as investment capital, depreciation, operating and maintenance costs, rate of return, payback period, sensitivity analysis, and the time value of money. These are not the macro-economic issues typically covered in general university economics courses, but are ideally learned in an engineering context, and are extremely influential factors for successful design.

  Cost-estimation is also a valuable skill for the competent design engineer. In the early stages of the design process, prior to the completion of engineering drawings that can be used for purchasing quotations, engineers must make design decisions based on an estimate of component or process costs. Experience, whether in industry or as part of an undergraduate design project, is a significant factor in developing cost estimation skills.

Design engineers are often involved from the conceptual stage of a project through to its implementation. Basic business skills, including market surveys, focus groups, and competitive product benchmarking, are valuable assets. Whether taking direct responsibility for these activities, which may be the case for an engineer in a small company, or working cooperatively with others in a multidisciplinary team, the ability to understand customers' needs and preferences, and consideration of overall business strategy are valuable skills in effective engineering design.

# Chapter 6

# Conclusions

The essence of professional engineering is captured in the definition of *design competency*. Competency is complex and profound, yet also a living entity that evolves with professional practice. If engineering science can be defined as the body of knowledge that helps the engineer find the performance characteristics of a given artifact, then engineering design may be defined as the body of processes by which the engineer finds the artifact that delivers the desired performance. It follows that innovation becomes the search for new artifacts from both engineering science and engineering design. Artifact is used here as a universal term to embody the design product at almost every level, including component, system, or process.

Understanding of engineering design competency is essential both to track the evolution of professional engineering practice and to select key elements for the education of practitioners. For those in industry and academe who are stake-holders in internationally competitive engineering education, the knowledge of required competency levels combined with state-of-the-art synthesis processes is crucial in order to guide the continuous improvement and advancement of engineering education. As discussed in this document, design competency can provide the necessary foundation for the ongoing renewal of undergraduate curricula in engineering; however, there is a need for Canadian universities to upgrade the current quality of design competency.

The use of advanced sizing-and-optimization tools in design processes is taught in every engineering discipline in Canada. If one considers these tools as those of cooks (who produce food for the masses), then chefs (who create delicacies) are those who use these processes to find key innovations, those that drive the country's economic competitiveness. The above examination of the engineering design competency suggests that Canadian engineering schools need to develop more tools for chefs, that is, skills for those capable of producing key innovations that will fuel success in the global marketplace.

## 6.1 Future Work

This document discussed extensively design engineering competency and identified the knowledge and skills required for competent and design-ready engineering graduates. To implement design competency in current and future engineering programs, a number of issues and challenges must be addressed, which may touch the very foundation of university traditions and operations. These include the current university reward policies, the academic program development and approval processes, the traditional engineering education models, the engineering accreditation requirements and processes, the academic culture in Canadian engineering schools, and so on.

It should be recognized that a significant effort has been made by Canadian engineering schools in promoting quality and excellence in engineering education. Traditionally, the enhancement of quality in engineering education has been achieved by providing high-quality instruction, excellent laboratory facilities, and relevant tutorials and assignments. Improvement has mainly relied on individual academics' willingness and ability to deliver quality instruction and on the school's culture and resources. However, the implementation of the engineering design competency model in the current engineering education system would challenge academia and would require a much broader debate of the fundamental values of the academic system. We claim that the identified engineering competency knowledge and skills cannot be effectively taught and, correspondingly, developed in the traditional classroom setting, or even within the current programs. Contentious issues must be thoroughly examined, such as: university reward policies, including tenure and promotion; research excellence versus design innovation and development; original research and high-quality of publications versus innovative products, processes and systems; individual teaching excellence versus the creation of innovative educational programs with a multi-teaching, experiential learning and expert coaching format; individual course ownership and accountability versus team teaching and responsibility; specialty versus broadness; a four-year program versus a five-year program with internship and integrated graduate and undergraduate programs; academic performance versus student involvement and, so on and so forth.

New thinking towards engineering education, the academic system, and research and innovation may be needed to effectively drive the Canadian engineering education to a new model that will produce engineering graduates who are design-ready innovators and lifelong continuous learners with the required engineering competencies. These graduates will be ready for global competition and will have the ability and the capacity to lead Canadian industry to effective participation in the world marketplace.

The NSERC Design Engineering Chairs Group wishes that this design competency work serve as a basis for ongoing debates and **discussions on design engineering education and innovation, the subsequent development of new engineering curricula and programs**, institutional reforms and public recognition of the significance of design engineering to ensure that Canadian engineering graduates possess the capability and capacity to lead engineering innovation in the 21st century and beyond.

The views exposed here are inclusive in that they pertain to all engineering disciplines. The competency items that we have put forth are intended as a blueprint for a Canadian design curriculum, to serve as a reference source for engineering educators, decision-makers and the stake-holders at large.

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