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Meeting the CDIO requirements: an international comparison of engineering curricula

Perry Armstrong†, Johan Bankel‡, Svante Gunnarsson*, John Keesee & Pat Oosthuizen*****

Queen's University Belfast, Belfast, Northern Ireland, United Kingdom†
Chalmers University of Technology, Göteborg, Sweden‡
Linköping University, Linköping, Sweden*
Massachusetts Institute of Technology, Cambridge, United States of America**
Queen's University, Kingston, Canada***

ABSTRACT: In this article, the *Conceive – Design – Implement – Operate* (CDIO) Syllabus and CDIO Standards are introduced, and the question is posed as to whether or not national circumstances affect the ability of engineering programmes to meet CDIO requirements. In particular, the extent to which representative programmes from the USA, Canada, Sweden and the UK cover the CDIO Syllabus is assessed and conclusions are drawn. The international applicability of the CDIO Syllabus also depends on the absence of conflict between the syllabus and national accreditation criteria. Based on the countries considered, the authors suggest that no conflict exists. Furthermore, it is argued that the CDIO Syllabus is aspirational and, as such, it complements the threshold requirements of national accreditation criteria. It is also argued that the CDIO Syllabus, coupled with the CDIO Standards, could form the basis for an international benchmark that would co-exist with any future global accreditation criteria and would serve to continuously improve engineering education.

INTRODUCTION

The collaborators in the *Conceive – Design – Implement – Operate* (CDIO) Initiative have developed an approach to reforming engineering education that is based on two main elements, namely: the CDIO Syllabus and CDIO Standards [1]. The CDIO Syllabus is an organised list of the areas of knowledge, skills and attributes that an engineering graduate could reasonably be expected to possess. It is intended to be generic in the sense that it is independent of both the country and engineering discipline involved.

The main sections of the CDIO Syllabus, which has two further levels of detail, are listed below:

- Technical knowledge;
- Personal and professional skills:
  - Engineering reasoning and problem solving;
  - Experimentation and knowledge discovery;
  - System thinking;
  - Personal skills and attributes;
  - Professional skills and attitudes.
- Interpersonal skills:
  - Teamwork and leadership;
  - Communication;
  - Communication in foreign languages.
- Product and system building knowledge and skills:
  - External and societal context;
  - Enterprise and business context;
  - Conceiving;
  - Designing;
  - Implementing;
  - Operating.

The CDIO Standards focus primarily on the delivery of an engineering programme, rather than its content. Among other issues, they address the design of the curriculum, the teaching, learning and assessment methods used, the need to upgrade faculty skills, and the importance of continuous improvement. The titles of the 12 CDIO Standards are listed below:

1. CDIO as Context;
2. CDIO Syllabus Outcomes;
3. Integrated Curriculum;
4. Introduction to Engineering;
5. Design-Build Experiences;
6. CDIO Workspaces;
7. Integrated Learning Experiences;
8. Active Learning;
9. Enhancement of Faculty CDIO Skills;
10. Enhancement of Faculty Teaching Skills;
11. CDIO Skills Assessment;
12. CDIO Program Evaluation.

The initial purpose of this article is to assess the extent to which national circumstances affect the ability of engineering programmes to meet the requirements of the CDIO Syllabus. Specific examples of engineering programmes are analysed in order to examine the implications for the CDIO Syllabus. The possibility of conflict between national accreditation criteria and the CDIO Syllabus is also addressed. The discussion that follows leads to the assertion that CDIO requirements could play an important international role, which would complement the international accreditation criteria likely to emerge over the coming years.

AN ANALYSIS OF REPRESENTATIVE PROGRAMMES

Individual engineering programmes are now compared in terms of the extent to which they meet the needs of the CDIO Syllabus. The specific programmes considered are as follows:

- Mechanical engineering at Chalmers University of Technology, Göteborg, Sweden (CHA);
- Mechanical and materials engineering at Queen's University, Kingston, Canada (QUC);
- Mechanical and manufacturing engineering at Queen's University, Belfast, UK (QUB);
- Applied physics and electrical engineering at Linköping University, Linköping, Sweden (LIU);
- Aeronautics and astronautics at Massachusetts Institute of Technology, Cambridge, USA (MIT).

For comparison, the timetabled hours or student credits for each course in the above programmes were assigned to one or more of the main sections of the CDIO Syllabus. The totals obtained for each section of the syllabus were then converted to percentages of the total hours or credits available. The results are presented in Table 1.

Table 1: Percentage of the curriculum devoted to sections of the CDIO Syllabus.

	Mechanical Engineering				
	CHA	QUC	QUB	LIU	MIT
Topic Heading	%	%	%	%	%
1.1.1 Mathematics	15.5	12.0	5.2	29.7	12.1
1.1.2 - 4 Science	16.3	14.8	2.1	12.5	12.1
1.2 Core Engineering Knowledge	13.6	27.6	31.3	11.3	20.0
1.3 Adv. Engineering Knowledge	11.8	10.4	16.7	19.4	13.0
1. Maths, Science & Engineering	**57.2**	**64.7**	**55.2**	**72.8**	**57.3**
2. Personal & Professional Skills	**7.6**	**3.4**	**4.8**	**7.2**	**3.7**
3. Interpersonal Skills	**2.3**	**3.0**	**2.5**	**3.4**	**3.7**
4.1 The External & Societal Context	7.9	5.4	3.1	1.9	0.1
4.2 The Enterprise & Business Context	8.1	1.7	5.2	1.9	0.0
4.3 Conceiving	2.7	5.4	2.1	2.5	1.7
4.4 Designing	6.8	11.4	14.6	4.7	5.8
4.5 Implementing	4.8	3.8	8.3	4.7	2.5
4.6 Operating	2.7	1.2	4.2	0.9	1.0
4. Product and System Building	**32.9**	**28.9**	**37.5**	**16.6**	**11.1**
Other					**24.2**

In the case of Sections 1 and 4 of the syllabus, cumulative totals are shown in the bold rows. It should be noted that individual courses were assigned to the section or sections of the syllabus that reflected their primary learning objectives. Hence, a science course may include a team-based assignment or may incorporate the teaching of a personal skill, but all of the course hours or credits are assigned to the science section of the syllabus.

Standalone projects, such as capstone projects, need a different approach, since they are not normally associated with a particular section of the CDIO Syllabus. Hence, for projects only, the course hours or credits were distributed among various sections, depending on the nature of the project. An additional row, entitled *Other*, is included in the table in order to record the fact that engineering students at the MIT also take courses in the humanities, arts and social sciences (HASS).

An examination of the data in Table 1 leads to the following observations:

- The fact that UK students specialise (at A Level) before entering university significantly reduces the need to teach underlying mathematics and science topics in engineering degree programmes;
- The HASS courses in the MIT programme significantly reduce the time available to cover the CDIO Syllabus;
- Coverage of *the External & Societal Context* at the MIT is limited to contributions from capstone projects (although it could be argued that some of the HASS content is relevant to this section of the syllabus). The other programmes include *dedicated* courses that address *the External & Societal Context*. The Chalmers programme, for example, includes a course on *Environmental and Energy Systems* and Linköping University offers a course on *Man, Technology and Society*. Queen's (Canada) provides coverage through its *complementary studies* courses, and Queen's (UK) covers relevant topics in its *professional studies* courses;
- The situation is similar in the case of *the Enterprise and Business Context*. As before, the MIT deals with this in its capstone projects, while the other programmes address relevant topics directly. Queen's (UK) again uses its *professional studies* courses, this time to cover economics, accountancy, management and marketing. Chalmers provide courses on economics and *Industrial Production and Organisation*, and Queen's (Canada) and Linköping include courses on economics;
- *Designing* is often developed through project work, but the mechanical engineering programmes at Chalmers, Queen's (Canada) and Queen's (UK) feature dedicated courses on design. The Queen's (Canada) programme, for example, includes courses on *Design Techniques* and *Machine Design*, and *Engineering Design* is taught in each of the first three years at Queen's (UK);
- *Implementing* also tends to receive more attention in the mechanical engineering programmes through courses that deal directly with manufacturing systems and processes. The presence of dedicated courses in both design and manufacturing in the mechanical engineering programmes results in the high percentages for *Product and System Building* shown in Table 1.

The above analysis indicates that national differences do influence the extent to which a programme can meet the requirements of the CDIO Syllabus. In the case of the MIT programme, the need to teach underlying mathematics and science subjects, plus the time allocated to the HASS component, leaves limited scope for dealing with topics in the syllabus through dedicated courses.

In contrast, Queen's (UK) does not have to teach as much mathematics and science, and has the advantage that the curriculum already includes *professional studies* courses. Hence, there is more time available and more opportunities exist to provide dedicated courses on a range of syllabus topics.

Queen's (Canada) has an accreditation requirement to set aside curriculum time for *complementary studies*. This provides some scope for addressing non-technical topics. In the absence of a formal accreditation system, the Swedish programmes have the option of including courses on topics concerned with the external, societal, enterprise and business context.

However, it is also apparent from the above analysis that the engineering discipline involved has a significant influence on the extent to which a programme can cover the CDIO Syllabus. In particular, mechanical engineering based programmes tend to automatically include courses that contribute to the *designing* and *implementing* sections of the syllabus.

In cases where there are limited opportunities for covering topics in the CDIO Syllabus through dedicated courses and other approaches need to be adopted. In Table 1, the curriculum time devoted to project work was distributed among various sections of the CDIO Syllabus. This serves as a reminder that projects provide the most obvious alternative to dedicated courses, as a *vehicle* for covering syllabus topics. Apart from product and system building skills, a wide range of personal, professional and interpersonal skills can be developed in well-conceived projects. Students can also gain a greater awareness of external, societal, enterprise and business factors in broadly-based projects that are not restricted to technical issues.

The CDIO Standards provide a further alternative when it comes to covering syllabus topics. CDIO Standard 7 calls for *integrated learning experiences* that address syllabus topics within disciplinary courses, ie courses in mathematical, scientific and engineering subjects. In effect, a *dual use of time* approach is advocated whereby students' skills are developed without reducing the coverage of disciplinary subjects. The development of Instructor Resource Modules (IRMs) within the CDIO Initiative is designed to provide support for faculty who adopt this approach [1]. The dual use of the time approach has already been adopted within the programmes at the MIT and Swedish universities (although this is not reflected in the data presented in Table 1). In fact, it is a CDIO requirement to adopt this approach, as evidenced by its inclusion in the CDIO Standards. Among other reasons, it is argued that students will appreciate the relevance and potential applications of a CDIO topic if it is developed within the context of a disciplinary subject.

From the above comments, it can be concluded that all programmes should seek to embed CDIO Syllabus topics in disciplinary courses as integrated learning experiences. In addition, all programmes should fully exploit project work as a vehicle for covering syllabus topics (significant project work has to be included in the curriculum in order to meet CDIO Standard 5). As has been demonstrated, the scope for addressing syllabus topics through dedicated courses will depend on national factors and the specific engineering discipline involved. In a particular case, it is likely that all three approaches will be utilised in order to cover the comprehensive list of topics in the CDIO Syllabus. However, each programme will require an individual strategy that employs a unique combination of the three approaches mentioned above.

ACCREDITATION SYSTEMS

Of the countries considered in this article, the USA, UK and Canada have accreditation systems for engineering education. Accreditation in the USA dates back to 1932 and, over the ensuing decades, the tendency was for accreditation criteria to become more detailed and prescriptive. However, there was a major change in direction when the Accreditation Board for Engineering and Technology (ABET) introduced the current EC2000 accreditation criteria, which focus primarily on student learning outcomes [2].

In the UK, accreditation was first introduced in the 1960s and the criteria became increasing prescriptive as they had in the USA. However, the same change to outcomes-based criteria occurred with the publication of UK-SPEC in 2004 [3].

The Canadian Engineering Accreditation Board (CEAB) is responsible for accrediting programmes in Canada [4]. In contrast to the USA and UK, the CEAB has not made the transition to outcomes-based criteria. Instead, minimum requirements are set for the time devoted to mathematics, basic science, engineering science, engineering design and *complementary studies*.

Sweden does not have a formal accreditation system for engineering programmes. However, a national programme for quality assurance was introduced in 2001 in order to evaluate degree programmes in all disciplines [5]. It is of note that the national agency recently adopted the CDIO Standards as an instrument for the continuous improvement in engineering programmes. The intention is that programmes will be self-rated against the CDIO Standards, and actions identified to increase the rating and improve the programme. The adoption of the Standards for programme evaluation highlights the fact that there are matters related to pedagogy, curriculum structure and course design that affect the student learning experience, but are not normally assessed as part of the accreditation process.

With increasing globalisation and the need to ensure the international mobility of engineers, it is not surprising that quality assurance and accreditation are developing an international dimension. In a recent development, Europe-wide accreditation criteria were published for engineering programmes. The EUR-ACE project reviewed accreditation procedures in 19 European countries and generic European criteria were published in 2005 in the form of a set of agreed learning outcomes [6]. The learning outcomes are similar to, but noticeably less specific than, the UK-SPEC criteria. This is likely to be the case with any international criteria since compromise is invariably required to obtain international agreement. Developments are also occurring outside Europe to move towards international criteria and it is possible that a global accreditation system will eventually emerge [7].

ACCREDITATION AND THE CDIO REQUIREMENTS

Satisfying accreditation criteria will inevitably take precedence over meeting the needs of the CDIO Syllabus. Hence, there is a potential problem in the USA, UK and Canada when it comes to satisfying CDIO requirements. In the case of Canada, there are prescriptive constraints on curriculum content that may reduce the scope for covering the CDIO Syllabus, but in the absence of required learning outcomes, there is no direct conflict between accreditation and the CDIO Syllabus.

However, conflict is possible between CDIO requirements and the ABET and UK-SPEC accreditation criteria. While it is recognised that the CDIO Syllabus is a list of topics, rather than a set of learning outcomes, potential conflict can be revealed by comparing syllabus topics with the topics that the ABET and UK-SPEC criteria refer to. However, close examination reveals that the problem does not arise, because the topics listed in the CDIO Syllabus adequately cover all of the topics referred to in the ABET and UK-SPEC learning outcomes. In fact, in each case, the CDIO Syllabus includes topics that are not referred to in the accreditation criteria. The

ABET learning outcomes, for example, make no overt reference to system thinking or the enterprise and business context, apart from its economic aspects.

Importantly, the CDIO Syllabus also resolves topics to a much finer level of detail than the ABET criteria. On the other hand, UK-SPEC lacks coverage of experimentation and knowledge discovery, ie research skills, and omits important personal and professional attributes. In addition, both sets of accreditation criteria focus on design as the main area of engineering practice and there is a lack of recognition that professional engineers are engaged in the complete *Conceive – Design – Implement – Operate* lifecycle of products and systems.

It is important to acknowledge that there is a fundamental difference in intent between accreditation criteria and CDIO requirements. The purpose of accreditation is to ensure that engineering programmes meet a minimum standard and hence accreditation criteria are threshold criteria. In contrast, CDIO requirements represent a higher standard or benchmark that CDIO collaborators believe is possible in engineering education. No programme currently covers all of the topics in the CDIO Syllabus, but full coverage should be a goal that programmes strive for through continuous improvement. In this sense, CDIO requirements are aspirational, and accreditation criteria and CDIO requirements are complementary, since there is no incompatibility between meeting minimum requirements and aspiring to a higher standard.

The international accreditation criteria that will evolve will undoubtedly be less stringent than current national criteria, as evidenced by the EUR-ACE requirements. Hence, it will become more important to have complementary international criteria that set higher targets for engineering education. CDIO requirements can fulfil this role, as they are the product of international collaboration and, as argued in this article, they are applicable internationally.

The adoption of the CDIO Standards in Sweden as a possible tool for continuous improvement is an interesting development. Quality assurance agencies involved in accreditation have tended to avoid pronouncements on pedagogical issues. Yet it is clear that the quality of an engineering programme depends on factors such as the teaching, learning and assessment methods used. It could, therefore, be argued that an international benchmark, of the type proposed above, should be based on both the CDIO Syllabus and CDIO Standards. Again, the requirements would be aspirational and the CDIO Syllabus, as well as the CDIO Standards, would be employed as an instrument for continuous improvement in the same way that the Swedish National Agency for Higher Education currently utilises the Standards. However, further *field testing* of the CDIO Standards and syllabus should first be considered within the CDIO Initiative.

CONCLUSIONS

An analysis of representative programmes has shown that engineering curricula vary in the extent to which they cover CDIO Syllabus topics. In particular, national factors and the discipline involved dictate the scope for addressing topics through dedicated courses. However, alternative approaches are available that involve embedding topics in project work or in disciplinary courses as integrated learning experiences. In a particular case, a strategy is needed, which adopts the combination of approaches that best suits national circumstances and the engineering discipline involved.

The authors have considered whether adherence to the CDIO Syllabus conflicts with national accreditation criteria. A close examination shows that the CDIO Syllabus covers a more extensive range of topics than those referred to in the ABET or UK-SPEC criteria. In this sense, it is more demanding and represents a higher standard that complements the threshold requirements of national accreditation criteria.

Furthermore, the CDIO Syllabus is applicable internationally and is likely to be much more comprehensive than any future international accreditation criteria. It could, therefore, form the basis of an international benchmark for continuous improvement in engineering education. Based on the Swedish experience, this proposal would be strengthened if the international benchmark coupled the CDIO Syllabus with the CDIO Standards. Further field testing may be needed, but a benchmark that engineering programmes can aspire to is more likely to improve the quality of engineering education than the baseline requirements set by any future global accreditation system.

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