Engaging the CDIO framework in Chemical Engineering Education

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Abstract*: In 2008, The Australian Learning and Teaching Council (ALTC) sponsored report by Robin King, Engineers for the Future: Summary and recommendations, summarily reported on the state of the Australian engineering educational system and proposed a set of six recommendations to address future challenges. Adoption of the CDIO framework has been one of the numerous specifically proposed actions that can be undertaken, and is as such, the focus of this paper. This paper presents our specific engagement with the CDIO approach in the discipline of Chemical Engineering within the Australian context by mapping the CDIO Syllabus with the Institution of Chemical Engineers' (IChemE) recommended learning competencies. We specifically outline our Unit level adoption of CDIO Standards most appropriate and realistic to our immediate context and our approach to curriculum development and integrating methods of teaching, learning, assessment and feedback.*

Introduction

In 2008, The Australian Learning and Teaching Council (ALTC) sponsored report by King (2008), *Engineers for the Future: Summary and Recommendations*, summarily reported on the state of the Australian engineering educational system and proposed a set of six recommendations to address future challenges. The authors were drawn particularly toward recommendation 3: Implement best practice engineering education. This recommendation entreats engineering educators to explore and adopt systematic and holistic educational design practices with learning experiences and assessment strategies that focus on delivery of designated graduate outcomes based on pedagogically sound, innovative and inclusive curricula (King, 2008).

Adoption of the Conceive-Design-Implement-Operate (CDIO) framework has been one of the numerous specifically proposed actions that can be undertaken, and is as such, the focus of this paper. Uptake of the CDIO curriculum design model has been identified by Cameron (2009) as one of the key processes that can drive alignment and synergies within curriculum development and also help enthuse, engage and inform students. Campbell, Dawes, Beck, Wallace, Dansie and Reidsema (2009) inform us of the presence of a growing community of CDIO practitioners in the Australasian region and the potential scope of mapping the CDIO syllabus within the Australian context.

In an attempt to understand what constitutes best-practice Chemical Engineering Education in the department, during first semester (February-June) 2009, the authors decided to explore problem-based learning (PBL) as a teaching and learning initiative within its undergraduate chemical engineering course, particularly in one of the final year units, Risk Management. The introduction of PBL was prompted at the time by the keen desire to address recent industry feedback regarding the perceived need for graduate chemical engineers with improved skills in problem-solving, critical thinking, and interpersonal skills particularly teamwork and communication. The authors found the experience of facilitating PBL intensely demanding. The above experience, although productive and encouraging, made the authors recognise the limitation of relying solely on an active learning method such as PBL to improve the quality of teaching and learning disciplinary content and skills. Findings emerging from this teaching and learning initiative have been documented in the authors' previous work (see Karpe. Maynard and Ray, 2009).

It became apparent that in order to successfully improve teaching and learning quality within this particular unit of study an entire teaching and learning framework with an appropriate curriculum model would be necessary. It is then that the authors sought their solution in the CDIO approach. This paper addresses how the authors have chosen to engage the CDIO initiative in an earnest effort to address recommendation 3 of the ALTC report mentioned earlier.

Engaging CDIO

At the outset it is essential to clarify the nature of this CDIO engagement in relation to the CDIO Standards. Crawley, Malmqvist, Ostlund and Brodeur (2007) declare that full engagement of CDIO occurs only when there is explicit agreement of faculty to transition to a CDIO program and support from program leaders to sustain reform initiatives. Crawley et al (2007) assert this implies a challenging fundamental cultural shift. The department of Chemical Engineering has been delivering a very traditional curriculum providing graduates with a strong practical orientation for the past 25 years. Currently the authors are the only change agents within the department keen to explore the CDIO initiative through this pilot study. It is hoped that the benefits from this engagement can be showcased to all departmental faculty in the near future to effect full CDIO engagement. There is already growing recognition and support from the course leaders. Crawley et al (2007) provide an excellent starting resource for practitioners interested in understanding how the CDIO framework can be applied to stimulate engineering education reform. The authors have currently limited their engagement to adoption of standards most relevant and realistic within the immediate institutional and teaching and learning context. This consists of a unit level adoption of the CDIO philosophy (Standard 1), Curriculum development (Standard 2 and 3), Methods of teaching and learning (Standards 7 and 8), Assessment and feedback (Standards 11).

The CDIO concept promotes the notion that “learning activities are crafted to support explicit pre-professional behaviours” (Crawley et al, 2007). What are the pre-professional behaviours of competent graduate chemical engineers? The authors have chosen to be directed in this regard by the view of the Institution of Chemical Engineers (IChemE) which aims to recognise and share best practice in the university education of chemical and biochemical engineers (IChemE, n.d). The IChemE concentrates upon assessment of learning outcomes (i.e. what is **learnt** by students) rather than traditional methods of specified degree programme content (i.e. what is **taught** to students). According to the IChemE accreditation guide (IChemE, n.d), students graduating from an accredited programme in chemical engineering must have: Knowledge and understanding, Intellectual abilities, Practical skills, and General transferable skills. These represent high-level outcomes which can be further defined in the chemical engineering context by focusing on a set of broad areas of learning which need to be clearly taught in all programmes seeking IChemE accreditation (Table 1). Essentially then, chemical engineering graduates from IChemE accredited courses will need to exhibit the four high-level outcomes in relation to each of the broad learning areas (Table 1) at a Bachelor or Master level degree course.

Table 1: IChemE Learning Outcomes Descriptors taken from the Accreditation Guide

	IChemE Learning Outcome	Descriptors
A	Underpinning mathematics and sciences (chemistry, physics, biology)	Students' knowledge and understanding of mathematics and science should be of sufficient depth and breadth to underpin their chemical engineering education, to enable appreciation of its scientific and engineering context, and to support their understanding of future developments
	Core Chemical Engineering	Students' knowledge and understanding of the main principles and applications of chemical engineering. Areas of learning include: Fundamentals, Applied quantitative methods and computing, Process and product technology, Systems, Process safety
	Advanced Chemical Engineering (Breadth and Depth)	In terms of depth IChemE expects Masters level student with a deeper understanding than previously acquired from first exposure to a topic earlier in the degree programme, taught to Bachelor level standard. In terms of breadth IChemE expects Masters level student with exposure to topics additional to those that would normally be considered as core chemical engineering.
B	Engineering Practice Skills	Graduates must understand the ways in which chemical engineering knowledge can be applied in practice, for example in: operations and management; projects; providing services or consultancy; developing new technology
C	Design Practice Skills	Chemical engineering design is the creation of process, product or plant, to meet a defined need. It includes process design and troubleshooting, equipment design, product design and troubleshooting, and system design. Students develop their powers of synthesis, analysis, creativity and judgement, as well as clarity of thinking.
D	Embedded Learning (Sustainability, SHE, Ethics)	Students must acquire the knowledge and ability to handle broader implications of work as a chemical engineer. These include sustainability aspects; safety, health, environment and other professional issues including ethics; commercial and economic considerations etc.
E	Embedded Learning (General Transferable Skills)	Chemical engineers must develop general skills that will be of value in a wide range of business situations. These include development of abilities within problem solving, communication, effective working with others, effective use of IT, persuasive report writing, information retrieval, presentation skills, project planning, self learning, performance improvement, awareness of the benefits of continuing professional development etc.

Having thus established what is the domain knowledge and skill set to be cultivated by a graduate chemical engineer, it became necessary to envision how disciplinary learning could emerge. IChemE "seeks to avoid prescription in these aspects", and informs that, regarding content delivery and assessment "the choice of methods is at the discretion of the university" and that "it is expected that the university will have its own formal procedures for assessment and maintain a robust quality assurance process to ensure that outcome standards are consistent and fair" (IChemE, n.d).

Evidently both CDIO and IChemE are non-prescriptive. IChemE offers "broad guidance on content" (IChemE, n.d), and CDIO "provide[s] a pallet of potential solutions" (Crawley et al, 2007). IChemE provides a vision to aspire toward; and the CDIO approach "becomes a collection of tools for program development and teaching support" (Gunnarson, cited in Crawley et al, 2007). This correlation is important to acknowledge in order to proceed further.

Towards Curricular Integration and Reform

It has been necessary to undertake the mapping of learning outcomes between CDIO and IChemE so as to enable a productive critical engagement with both. Page constraints only permit the presentation of the direct results of the mapping process. In Table 1 the IChemE Learning Outcome Descriptors are provided. In Table 2 the CDIO Syllabus Topics at Level 2 detail are mapped against IChemE Learning Outcome Areas (as described in Table 1). This mapping was based on the same principles used to map the CDIO Syllabus to the ABET Student Outcomes by Crawley et al (2007).

Table 2: CDIO Syllabus Topics mapped against IChemE Learning Outcome Areas

	CDIO Syllabus Topic	IChemE Learning Outcome (see Table 1)
Technical Knowledge & Reasoning	1.1 Knowledge of Underlying Sciences	A
	1.2 Core Engineering Fundamental Knowledge	
	1.3 Advanced Engineering Fundamental Knowledge	
Personal & Professional Skills & Attributes	2.1 Engineering Reasoning & Problem Solving	E
	2.2 Experimentation & Knowledge Discovery	E
	2.3 Systems Thinking	C
	2.4 Personal Skills & Attributes	C, E
	2.5 Professional Skills & Attitudes	D, E
Interpersonal Skills: Team & Communications	3.1 Teamwork	C, E
	3.2 Communications	
	3.3 Communications in Foreign Languages	-
Conceiving, Designing, Implementing & Operating Systems in the Enterprise & Societal Context	4.1 External & Societal Context	C,D
	4.2 Enterprise & Business Context	B
	4.3 Conceiving & Engineering Systems	B,C,D,E
	4.4 Designing	C
	4.5 Implementing	B,D
	4.6 Operating	B,D

This paper describes a process of applying the CDIO framework to a specific subject in a specific engineering discipline. It is necessary though, to acknowledge that no subject stands alone and that an effort needs to be made to situate the subject concerned within the CDIO context in terms of the whole program offered at any particular institution. Using the IChemE core engineering learning area to define content and the CDIO syllabus to define the appropriate learning outcome we have developed an Intended Professional Skills Progression table for a four year undergraduate chemical engineering degree course (Refer Table 3).

Table 3: Intended Professional Skills Progression over 4-yr Bachelor degree in Chemical Engineering

	CDIO Syllabus Topic	Y2/S1	Y2/S2	Y3/S1	Y3/S2	Y4/S1	Y4/S2
Technical Knowledge & Reasoning	1.2 Core Engineering Fundamental Knowledge	Process principles	Process engineering analysis	Process modelling & simulation	Process synthesis & design	Risk Management	Design project
Personal & Professional Skills & Attributes	2.1 Engineering Reasoning & Problem Solving	3	3	3	4	4	4
	2.2 Experimentation & Knowledge Discovery	2	2	3	4	4	4
	2.3 Systems Thinking	2	2	3	3	4	4
	2.4 Personal Skills & Attributes	2	3	3	3	4	4
	2.5 Professional Skills & Attitudes	2	2	2	3	3	4
Interpersonal Skills	3.1 Teamwork	3	3	4	4	4	4
	3.2 Communications	2	3	3	3	4	4

In Table 3 selected CDIO syllabus topics are presented in the left section. In the section on the right, core chemical engineering study units are presented (vertical text) under the corresponding year and semester within a four-year engineering program. Also, Yn and Sn represents Year and Semester respectively where n = 2, 3, 4.

The assumptions supporting the Intended Professional Skills Progression table (Table 3) will now be elucidated. The common first-year of engineering study, also known as engineering foundation year (EFY) has been excluded. The EFY curriculum serves as a warm introduction to the profession of engineering as a whole rather than a full immersion or induction into any particular discipline. There is a greater emphasis on creating numerous learning opportunities for students to experientially develop personal, professional skills and attributes, and interpersonal skills during the EFY period. Greater exposure to specific disciplinary technical knowledge and reasoning is left to the remaining three years of study. The authors opine that the emphasis in the remaining years of study is so heavily weighted on technical knowledge acquisition and application that the opportunities to sustain and enhance the experientially developed skills of the foundational year are few and far between. This ill-serve our personal responsibility as educators to prepare student engineers for workplace problems.

There is a need to conceive engineering education more broadly. Jonassen, Strobel and Lee (2006) reveal that engineering work place problems have little to do with engineering; that in fact they are complex and ill-structured and that invariably the real constraints are "non-engineering" - time, budgets, cost, functionality, biases, preferences, codes and standards, legal restriction etc. It can be argued that as educators we cannot assume that exposing our students to well-structured, "engineering-only" (Jonasse, Strobel and Lee, 2006) problems will enable them to effectively transfer their learning to the resolution of complex, ill-structured workplace problems. Is there an alternative? Jonassen, Strobel and Lee (2006) contend that, rarely do practicing engineers recommend more engineering in the engineering curricula, rather, most of the engineers emphasised more instruction on client interaction, collaboration, making oral presentations, and writing, as well as the ability to deal with ambiguity and complexity. Inspired by the above pragmatist leaning, the authors felt it necessary to facilitate opportunities for their students to re-connect and nurture their experientially developed skill sets from their EFY experience. This is the reason underlying the authors' decision to selectively emphasise specific CDIO syllabus topics such as personal and professional skills and attributes, and interpersonal skills in the remaining years of study.

The numbers in the cells represent the expected student proficiency level based on the CDIO proficiency scale as suggested by Crawley et al (2007). For the purpose of clarity the rating scale linking the numbers or "scale points" (Crawley et al, 2007) to the corresponding levels of competence expected in the activities or experience of engineers is presented below.

1. To have experience or been exposed to;
2. To be able to participate in and contribute;
3. To be able to understand and explain;
4. To be skilled in the practice or implementation of;
5. To be able to lead or innovate.

The scale points indicated in table 3 are hypothetical and their selection (at least at this point in time) is a speculative enterprise. It is assumed that the students entering second year of study have had personal experiences in applying skills emphasised in the Intended Professional Skills Progression table, not just those resulting from within the context of their foundation year but also non-academic, social settings. Realistically the ability to lead or innovate will only come with several years of experience as a practicing engineer. It is much more reasonable to expect that students would graduate skilled in disciplinary practices so as to secure gainful employment.

Crawley et al (2007) indicate that the scale points designate "absolute" level of competence expected of practicing engineers. How does one compute the skill rating of every individual learner in dynamic learning environments in "absolute" terms? Since the authors are novice CDIO practitioners they have very limited expertise in how this computation is undertaken in an academic setting so as to be meaningful and beneficial. We hope that seasoned CDIO practitioners from within the academic community will share their expertise in this skill and thus lead us to not only greater understanding but also greater confidence in applying it.

It is important to note that from a pragmatic operational perspective, the Intended Skills Progression table provides the necessary framework to engage specific CDIO syllabus topics within immediately relevant disciplinary contexts that can be employed to facilitate learning. In other words, authors are now in a position to adapt the existing CDIO framework within the immediate chemical engineering disciplinary context. Owing to departmental constraints this exploration can only be undertaken in specific units that the authors deliver. More specifically, the aim has been to enhance the learning experience of students in the Year 4 unit – Risk Management. IChemE considers this topic to be integral to the study of chemical engineering systems, and expects students must understand the principles of risk and safety management, and be able to apply techniques for the assessment and abatement of process and product hazards (IChemE, n.d.).

It must be conceded that the nature of this unit has significantly influenced the authors' ability to realistically engage the CDIO approach. It was envisioned that learning within the unit be distinctly application oriented and provide students with opportunities to exercise their engineering judgement. Emphasis would be on, "principal concepts of risk management and the practical outworkings of those concepts" (Cameron and Raman, 2005). It was deemed necessary to, "show undergraduates how safety assurance is actually performed in industry" (Skelton, 1997). A systems oriented teaching approach would ensure students move gradually from "simple application of common sense and basic engineering skills" (Skelton, 1997) to "application of specialist safety analysis methods" (Skelton, 1997).

Since the CDIO approach is distinctly systems oriented, it has easily lent itself to the authors' teaching and learning cause. The CDIO syllabus topics offered greater clarity in the definition of learning outcomes, leading to better alignment between various assessment methods and the learning outcomes (Refer Table 4).

Table 4: Risk Management Unit Learning Outcomes mapped to CDIO Syllabus topic and Assessment Type

Unit Learning Outcome	CDIO Syllabus Topic Level	Homework Problem	Reflective Journal	Group Problem	Group Presentation	Concept Map	Test
Risk Management Knowledge	1.2	X		X	X	X	X
Reasoning & Problem solving	2.1	X		X	X		X
Knowledge Discovery	2.2	X		X			
Systems Thinking	2.3		X	X		X	X
Critical Thinking	2.4.4			X			X
Lifelong learning	2.4.6		X			X	
Teamwork	3.1.2			X	X		
Communication	3.2.2 3.2.6		X	X	X		X

Conclusion

At the end of the day what makes a difference is exactly what a student does and how they experience what they do (Boud, cited in Bryan and Clegg, 2006). Implementation of PBL during first semester (February-June) 2009 revealed that shifting to an alternative pedagogic method alone will not suffice in improving the quality of teaching and learning. The authors experienced that although their students were receptive to the alternative learning opportunities they took selective ownership of their own learning. An immediate need was then felt to address this issue holistically. This would involve conceiving curriculum, instruction and assessment to be aligned in a manner so as to complement one another. The authors recognised that the CDIO initiative offered a systems oriented approach to integrate the above mentioned three components to enhance the quality of learning within their unit. This initial engagement of the CDIO framework within the chemical engineering departmental context was undertaken during first semester (February-June) 2010. It has resulted in the confluence of teaching, learning, assessment, and feedback into a unitary process. The authors have been able to employ appropriate assessment activities which require active participation from the learners. A responsive feedback mechanism has also been developed in order to promote the emergence of a cooperative learning environment for the achievement of unit learning outcomes. Preliminary findings obtained from student learning satisfaction questionnaires and unit evaluation surveys have indicated very high satisfaction levels. It is beyond the scope and intent of this paper to present these findings. The impact of the application of the CDIO framework to the learning experience is proposed to be the focus of a forthcoming paper. It is envisioned that with the aid of seasoned CDIO practitioners within the Australasian academic community a thorough unit and program level evaluation could be undertaken in the near future to inform the department's continuous improvement process. This would take the department one step closer to establishing best practice chemical engineering education.

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