THE CHEMICAL ENGINEERING CDIO EXPERIENCE AFTER 5 YEARS OF IMPLEMENTATION

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ABSTRACT

This paper summarizes the curriculum re-design effort for the Diploma in Chemical Engineering of Singapore Polytechnic over the past five years since adopting CDIO in November 2006. We firstly present our 5-year implementation road map and overall approach to implementing CDIO. This documents our work in gap-analysis, skill mapping, curriculum innovation, while making some comparison to our curriculum prior to CDIO adoption.

Secondly, we discuss the challenges faced, focusing on two key areas: (1) Concern over reducing technical content and/or insufficient time to cover all technical content; and (2) concern over high workload and ability to teach "soft" CDIO skills. We then share important insights gained and our approach towards sustaining faculty CDIO capability. We share our findings on the effectiveness of our re-designed curriculum, in terms of student learning experience, student retention rate, and feedback from recent graduates. The major outcomes have been positive, based on the information collected. Thirdly, several critical success factors are identified, all of which had a common denominator: the *human dimension*. Specifically, this entailed the importance of leadership support, role of early adopters and education advisors, faculty mindset and managing student expectations.

Finally, some future developments and challenges in the journey ahead are discussed, especially consolidating and enhancing transferability of skills covered, introducing new skills, and resources required. We conclude that the most significant challenge is developing faculty CDIO capability and sustainability via continual improvement. Specific details of the latter are covered in a separate paper entitled "*Using CDIO Self-Evaluation for Quality Assurance and Accreditation*" prepared for this Conference.

KEYWORDS

Curriculum re-design, chemical engineering, program evaluation, critical success factors

<u>NOTE</u>: Singapore Polytechnic uses the word "courses" to describe its education "programs". A "course" in the Diploma in Chemical Engineering consists of many subjects that are termed "modules"; which in the universities contexts are often called "courses".

INTRODUCTION

The Diploma in Chemical Engineering (DCHE) of Singapore Polytechnic (SP) embarked on a journey to revise and reorganize – "revamp" – its curriculum using the CDIO Framework (Crawley, et al [1]) beginning late 2006. After about 15 months of preparation, a revised curriculum was rolled out in April 2008 for the Academic Year (AY) 2008. A full description of the overall approach taken at the commencement of the revamp effort, as well as the rationale for change (e.g. emergence of chemical product design, increasing importance of "soft skills" or "general transferable skills") and challenges encountered have been documented in various past CDIO papers [2].

This paper briefly discusses the work done by the DCHE team over the last five years, for the period April 2008 – April 2013. It presents the following: an implementation road map that was used to guide the process for the past five years, a general model of CDIO integration, gap analysis and skill mapping, major features of the revamp effort, challenges faced and insights gained, evaluation of student learning, critical success factors, continual improvement and efforts to ensure the sustainability via professional development. Finally, there is a summary discussion of future developments and challenges in the journey ahead.

IMPLEMENTATION ROAD MAP AND METHODOLOGY

We first customized the original CDIO syllabus from MIT and partners so that it is appropriate for SP's context of diploma-level education. The DCHE Course Management Team (CMT) prepared a 5-year implementation road map to guide its revamp effort, as shown in Figure 1.

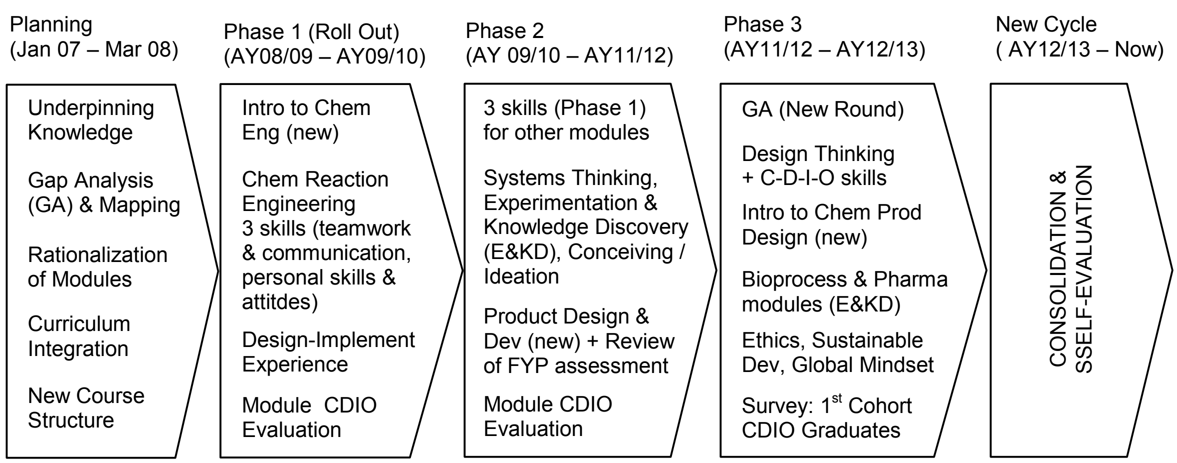

Figure 1. Road Map for CDIO Implementation in DCHE

Broadly, the first four years of the curriculum revamp effort can be viewed as consisting of a 2-prong approach as follows:

1. Integrating various 'soft' skills such as teamwork, communication, critical thinking, etc. (abbreviated as CDIO skills for the purpose of this paper) to provide a more holistic approach to engineering education for our students. This is largely achieved through systematic infusion of the CDIO skills into carefully designed learning activities in the laboratory sessions or assignments in selected core chemical engineering modules.

2. Integrating skills in conceiving, designing, implementing, and operating an engineering product, process or system (abbreviated as C-D-I-O skills to distinguish from the abovementioned CDIO skills) using chemical engineering principles. This involves specific changes in course structure whereby new modules are introduced through merging or removing existing overlapping or obsolete modules, and culminates in a more effective execution of the students' final year (capstone) project.

The general approach in integrating a selected CDIO skill into a chosen module is shown schematically in Figure 2. It can be seen that the process starts at the very top in terms of the course aims that strive to deliver the desired graduate attributes. This translates into a revised course structure designed to support the desired course aims.

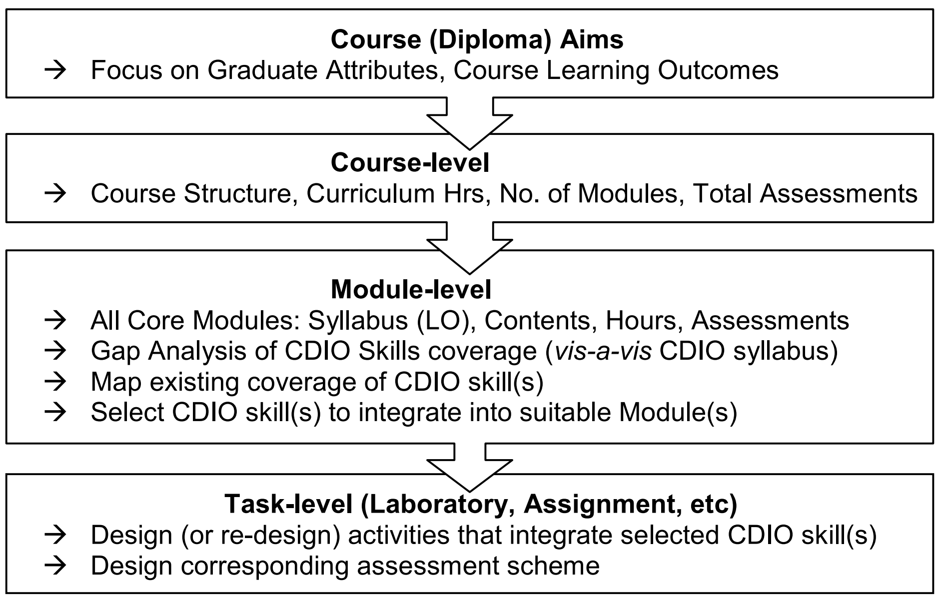

Figure 2. The General Approach of CDIO Implementation into Core Modules

All module syllabi were re-written to reflect the desired learning outcomes and group-moderated to ensure clarity. Tasks based on simulated real-world scenarios that engage students via active experiential learning were then designed.

At the time of writing this paper, we are into the "Consolidation" phase of our revamp effort. This will be elaborated in greater detail in later sections.

Gap Analysis, Skill Mapping & Integration

A gap analysis was conducted in which a core team of early CDIO adopters captured as baseline information where we stood in terms of what existing CDIO skills are already covered in our curriculum, and to what level of competency. The result from the gap analysis was a CDIO skill map that detailed the CDIO skills currently covered in which module(s). The CMT then inferred the level of competency expected from the tasks involved, drawing input from the faculty as well as other stakeholders, e.g. through industry surveys. We used the same 5-point scale of Crawley et al [1] for the expected level of proficiency in CDIO skills, but calibrated to the outcome expected for diploma-level graduates.

This skill map served as a basis for CMT to decide how best to integrate the CDIO skills in the most impactful manner. Figure 3 shows how we first identify the core chemical engineering modules (ellipses in red) deemed suitable to integrate a chosen CDIO skill. These are either modules with existing learning activities or having good opportunities to introduce CDIO skills.

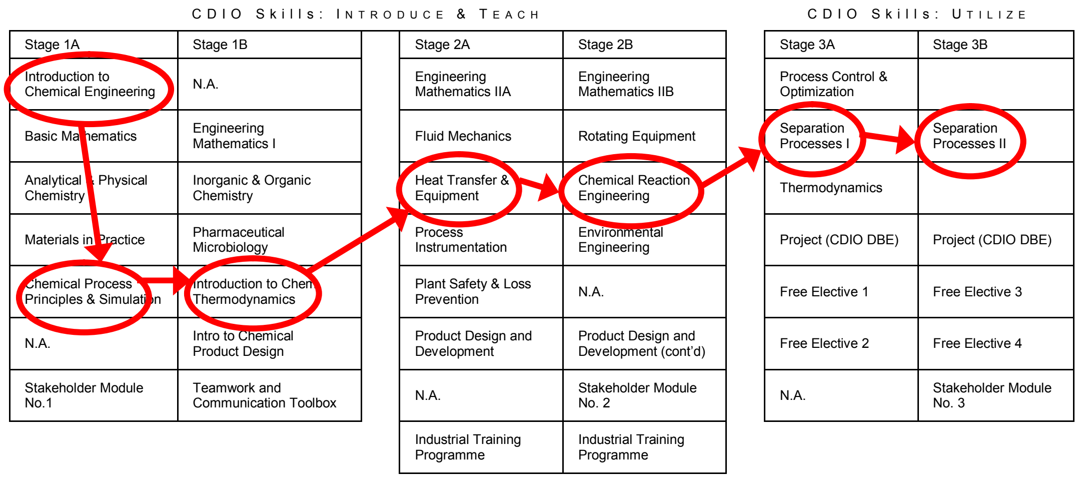

Figure 3. Integrating a selected CDIO skill across a three-year curriculum

We then systematically infused the selected CDIO skill into the modules. The general approach taken is to first introduce and teach students specific skills in Year 1, which are then extensively practiced in Year 2. By Year 3 they are expected to be able utilize the skills where appropriate and display skill transfer from one module to another.

MAJOR FEATURES OF REVAMP EFFORTS

In summary, the outcome of our adoption of CDIO resulted in an integrated curriculum that is delivered in an active, experiential manner. Typically, the integration method involves linking a core module with key concepts from other core modules and also integrating various CDIO skills (e.g., hypothesis testing, systems thinking, global mindset, etc.). We have also introduced chemical product design into our curriculum whereby skills in conceiving, designing, implementing and operating complex value-added (chemical) engineering products, processes, and systems in a modern, team-based environment (i.e. C-D-I-O skills) are tightly integrated from Year 1 to Year 3. Table 1 below summarizes the major differences in the curriculum before and after the adoption of CDIO. For specific examples on work done in each area, kindly refer to the references in Table 1.

Major features of our CDIO-enabled curriculum include the following:

1. Module syllabi are written in outcome-based learning objectives
2. Laboratory activities are re-designed as real-world job tasks whereby scenarios (reflecting possible future work environments) are created that contextualize the simultaneous applications of theories taught and CDIO skills in an active, experiential manner (see Box 1 for an example)

Table 1. Comparison of DCHE Curriculum after and before CDIO

S/N	With CDIO	Before CDIO
1	Outcome of student learning is determined by what the students are expected to do, i.e. job competency, consistent with our desired graduate attributes	Outcome is teaching-based, i.e. determined by what a faculty thinks students need to know, and "what one thinks students are capable of doing"
2	Approach is student-centered; delivered via active, experiential manner [3], [4]	Approach is teacher-centered; mode of deliver is mostly for transmission of knowledge
3	Year 1 module *Introduction to Chemical Engineering* (*ICHE*): introduces students to the profession and industry, roles and responsibility, typical job tasks	No such module: assumes students know what the discipline is about by virtue of their signing up for the diploma
4	Modules are integrated in terms of technical contents and CDIO skills to support the job competency	Modules cover only technical contents, largely "independent", compartmentalized learning and not integrative
5	CDIO skills integrated into core modules ([5], [6], [7], [8]) with a special "twinning" arrangement of a technical module with "soft" module [9]	CDIO skills taught separately in several separate standalone modules
6	Faculty teach both technical knowledge and skills, as well as CDIO skills, expanded role that include facilitation, coaching and mentoring	Faculty teach only technical knowledge and skills, mostly counseling role
7	Basic level of Design-Implement Experience in Year 1 (*ICHE*), intermediate level in Year 2 (*Environmental Engineering*) and Year 3 (*Chemical Reaction Engineering*), and advanced level in Year 3 *Final Year Project* (*FYP*)	Only *Final Year Project* (*FYP*) in Year 3
8	Balanced treatment of C-D-I-O elements: Year 1 *Introduction to Chemical Product Design* (with Design Thinking), Year 2 *Product Design & Development,* Year 3 *FYP* [10], [11]	Product design not explicitly taught. Few opportunities for Conceive, some Design, mostly Implement and Operate during some Year 3 *FYP*
9	Global Mindset [12], Ethics [13], Sustainable Development [14] integrated into core modules	No coverage of global mindset, ethics and sustainable development
10	Assessment of application of technical knowledge integrated with CDIO skills [15]	Assessment is heavy on testing technical knowledge, memory work

3. Same pilot plants are used in various modules or stages/years of study, so as to mutually reinforce and integrate concepts taught in different modules; as well as to break down (or at least reduce) compartmentalization of learning
4. Re-focusing of assessment from that of domain knowledge per se to key understandings and application of various topics taught in different modules
5. Suitable CDIO skills are infused throughout and assessed at all three stages of laboratory sessions: (a) Pre-, (b) During, and (c) Post-Experiment
5. Assessment of both technical knowledge and CDIO skills are integrated and carried out at the same time (see Box 2 for a technical presentation)
6. Customized assessment scheme for each laboratory activity, where both individual and team contributions are assessed (see Box 3)
7. Assessments are explicit with the use of rubrics for key performance areas

8. Expectations are briefed to students right at the beginning, where a "CDIO Learning Guide" is given to each student, and reinforced over the semesters
9. Feedback is provided immediately where possible (e.g. oral presentation, teamwork) and written reports are marked, comments given and returned within two weeks

Box 1. Sample Simulated Real-World Scenario for *Separation Processes*

You work in *Damsolid Packings Pte Ltd*, a company specializing in packing materials for unit operations such as distillation, absorption, extraction etc. Each new packing design is to be tested for its loading and flooding characteristics, to obtain a so-called flooding curve as shown in Figure 1. Such testing is usually done using air as the gas stream and water as the liquid stream.

You and your team are tasked with the responsibility of performing such testing. The theory behind loading and flooding phenomena is given in **Appendix 1**. Standard operating procedures for conducting such testing are given in **Appendix 2**. At the end of each testing, your team is to submit a technical report of the test results and make appropriate recommendation on the particular region of acceptable operation for the packing tested.

Your company received an enquiry from a potential customer, *Clean & Cheap Energy Systems Pte Ltd* (*C&C* in short) about suitable packing that can be used to remove ammonia from a fuel gas stream before supplying to its fuel cells systems. The solvent is phosphoric acid. Your boss, Mr. Kao Bin Phuay, informed that a *C&C* representative, *Mr. Wally Hartopleeze*, who is the company Technical Manager, will drop by the laboratory and you will be required to give him a quick presentation about how the company go about testing its packings.

Box 2. Integrated Assessment of Technical and CDIO Skills

<u>Pre-Experiment Assessment</u>: Oral Presentation (any one member to present)

Your supervisor informed that the President of *InvestigatAll Institute of Chemical & Life Sciences*, Dr. Boh See Kan, is dropping by to see how the interns are doing. In your team, prepare a **2-minute** oral presentation, about your assignment.

1. Explain the factors that you had considered in planning for the presentation. (3 marks)
2. Deliver your presentation. You will be assessed for both accuracy of technical content and your ability to deliver it in a clear and logical order. (5 marks)

KEY CHALLENGES FACED AND INSIGHTS GAINED

We faced numerous challenges in our revamping effort. The focus here is to share some of the most significant challenges related to the faculty who are the "real actors" in the CDIO journey, as well as how the CMT attempted to overcome them.

Reducing technical content and/or insufficient time to cover content

There is always concern among faculty of insufficient time to cover the existing curriculum and the reluctance and/or resistance to reduce technical content. We therefore decided to integrate CDIO skills using the laboratory (practical) components of the core modules. There is usually some "slack" time during the 3-4 hours of practical lessons. This also makes good sense, as it is more challenging to try the integration effort in a lecture with some 60 students. Furthermore, the small class size (20 students) coupled with extra manpower – there are 2 faculty in a typical practical lesson – makes for more effective facilitation.

Box 3. Sample Assessment Questions – Individual vs Team Contribution

(Teamwork is promoted by requiring each member to contribute to total team score in *Group Questions*)

Individual Question: (4 marks)

Each member is to locate and identify one safety device in the plant, and explain its relief scenario.

Group Questions: Discuss as a team, with each question answered by different member. Same marks for the whole group.

1. Identify two sources of errors in the experiment and explain how they can affect the results obtained. (4 marks)
2. Based on the results obtained, explain (*no calculations required*) how pressure drop can be utilized to obtain the column diameter in equipment design. Bring along any relevant correlations or diagrams from your literature research. (6 marks)

   ....

5. Explain what characteristics the packing material must possess that make it suitable for *C&C*'s application. Support your answer with relevant literature materials. (6 marks)

We also leveraged on existing laboratory practices that requires students to prepare themselves well before attending the laboratory sessions. This is part of the independent learning that we had been practicing in the past, well before the adoption of CDIO. Thus, by transferring much of the factual knowledge in a given module into background materials needed for the laboratory practicals we are able to free up some precious curriculum hours. This notion of not needing to teach students everything eventually resonates well among our faculty. We also "play" on their common complaints that students are not able to apply the theories taught. We showed that by placing the responsibility of learning squarely on the shoulder of students, through the re-design of learning tasks using CDIO, faculty can focus on evaluating students applications of theories learnt. It is therefore a case of not what or how much knowledge we teach, but rather the way we teach that allows learning to take place effectively.

High workload and ability to teach "soft" CDIO skills

Many faculty expressed concern over increasing workload – not least of all, they are now required to teach soft skills as well as technical domain knowledge – within the same core modules. This is indeed a real concern, as all of us are becoming increasingly overburdened with the plethora of administrative work that is now the norm in most educational institutions. Some faculty were also not comfortable in teaching the CDIO skills effectively and efficiently; as many perceived that these skills involved key knowledge from the fields of psychology, economics and, some would say, philosophy as well.

To address this concern, we first choose the three skills which are most familiar to everyone (the so-called "low-hanging fruits"): teamwork, communication, and personal skills and attitudes such as critical thinking and time management. Next, we relate the underpinning knowledge of these skills to the prior working experience of the faculty by first getting them to share some work-related situations where they need to use these skills; and then involving them in reviewing the underpinning knowledge. This, plus engaging them in writing clear learning outcomes for their respective module syllabus, enables a realization that these skills are already well-established generic skills for effective learning and performance in real work contexts – engineering or otherwise. There is therefore a sense of familiarity among the faculty – and they quickly come to the recognition that they actually possess such knowledge. Therefore, it become clear to them that while many of them had not consciously thought about teaching these skills explicitly, the notion of integrating them with subject content knowledge and teaching them was indeed quite doable.

Some useful insights:

1. By focusing the attention on laboratory practicals, we are able to set achievable targets for our faculty, making the process more manageable, i.e. not imposing unrealistic workloads; hence secures the required buy-in.
2. The gap analysis process, although a very time-consuming activity, is worth doing and worth doing well. Using a clearly written set of underpinning knowledge for the selected CDIO skills is very useful to help dispel wrong perceptions of these skills and what it takes to integrate and teach them in the context of chemical engineering education.
3. It is important to provide a platform for faculty to meet and discuss their work done in integrating CDIO into their modules, with the specific intention to leverage on prior learning
4. In essence, every laboratory practical session is unique. Often the practice of teaching CDIO skills is very situational, depending on presence of "teachable moments"
5. Related to the above, it is essential for faculty to possess good facilitation skills to help students learn in such "new" manner which can be uncomfortable for some; having accustomed to the less active, more traditional instructional methods.

CDIO EVALUATION, CONTINUAL IMPROVEMENT AND SUSTAINING FACULTY COMPETENCY

By the end of AY2010, we conducted further gap analysis to assess where we stood vis-à-vis our implementation goals. While we have made significant progress over the span of a few years, the task is far from over. Some new gaps had appeared from our adoption of design thinking SP-wide. There is also a growing recognition to sustain the competency of our faculty, especially in area of curriculum re-design using CDIO. To this end, established a Teaching and Learning (T&L) Unit within the school; staffed with several experienced CDIO adopters now serving as mentors to new faculty. This model had been piloted with several faculty and the results had been very encouraging [16]. It has now become the way the DCHE CMT induct new faculty into our CDIO-way of curriculum design and teaching.

The rest of this section deals with program evaluation, focusing on 3 keys areas: (1) student learning experience; (2) student retention rate; and (3) feedback from recent graduates. We did not include surveys of employers, and in fact are still deliberating if such an endeavor is worth undertaking. Our first cohort of "CDIO-trained" students graduated in March 2011, and all Singaporean males are then enlisted in the compulsory 2-year military service, while most Singaporean females and foreign students (both male and female) would embark on further studies in the universities. Hence, only a handful of students actually joined the workforce, and this tend to be students who are weaker academically, and perhaps also not so adept in other competencies as well. We are not sure if any meaningful results can be obtained from the employers at this point in time.

Student Learning Experience

We conducted a three-year longitudinal study to ascertain the students' learning experience for the first 3 years of implementation (AY2008 – AY2010). Each faculty also conducted surveys in his/her own module(s). Results from the study showed that students in general were receptive to the new way of learning and appreciate the opportunity to take part in curriculum re-design. The details of these surveys are covered in past CDIO papers.

Student Retention Rate

Table 2 shows the yearly progression rate and cohort success rate (CSR, defined as the percentage of students who successfully graduated within three academic years from the year of enrollment) for the last three academic years. The steady increase may suggest that the revamped curriculum has indeed led to an improvement in student retention rate.

Table 2: Yearly Progression Rate and Cohort Success Rate

	AY 2010-2011	AY 2011-2012	AY 2012-2013
Year 1 - Year 2 Progression Rate	93.22%	94.21%	
Year 2 - Year 3 Progression Rate	95.19%	93.64%	99.12%
Cohort Success Rate	77.86% (enrolled in AY2007)	83.48% (enrolled in AY2008)	86.44% (enrolled in AY2009)

Recent Graduates

We conducted a survey of graduates from selected student cohorts to ascertain the extent to which they experienced consolidation of their learning experience with DCHE in SP. Graduates were asked to rank, using a scale of 1 (poor) to 5 (excellent), how well the DCHE course has prepared them for key skill areas. The results are presented in Figure 4, categorized into three groups according to the year of graduation. The mean response suggests that, as a whole, there is an improvement in the graduates' perception of how well the course has prepared them over the years. Significant improvement is seen in "Oral Presentation", "Report Writing", "Systems Thinking", "Creative Thinking" and "Learning Independently".

CRITICAL SUCCESS FACTORS

Based our own experience over the last 5 years, we believe the followings are the most significant critical success factors:

- *Leadership* – Top management must provide its support, not just in additional manpower to support but for faculty who obtained lower feedbacks score resulting from his/her "experiment" with CDIO. It is also essential that the CMT leads the revamp effort, to provide the top-down direction while at the same time encourages bottom-up initiatives.
- *Early Adopters* – Not only do the early adopters contribute to the core team for gap analysis, they are also more receptive to adopt a pedagogy-driven process to execute the revamp effort. They also help to mentor new faculty in implementing CDIO in the new faculty's module(s).

- *Faculty* ("the rest of the masses") – To obtain buy-in, we conducted many briefings and training workshops, to clarify the revamp intent, share good practices, provide progress updates, as well as to reinforce that the revamp effort is "for real" and not another fad.
- *Education advisors* – Effective curriculum revamp requires faculty expertise in both domain knowledge and pedagogy. Discussions with the education advisor (often on one-to-one basis) had proven very effective at eliciting hidden or implied learning objectives desired by the module coordinator but not verbalised satisfactorily in written form.
- *Students* – We need to manage their expectations, especially for those who are more interested in learning the technical content; and wondered how some skills, such as creative thinking, can be important in their chosen field of study. We need to constantly explain, and reinforce at appropriate intervals, the importance of CDIO skills.

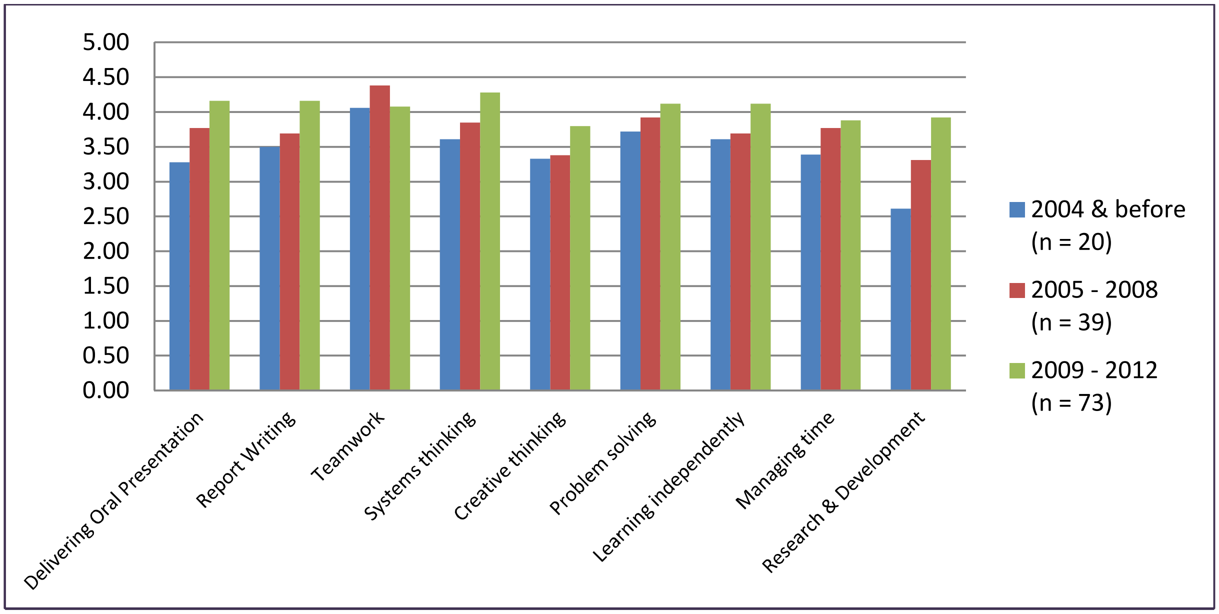

Figure 4: Survey results on how well DCHE has prepared graduates in various CDIO skills

FUTURE DEVELOPMENTS AND CHALLENGES

As shown in Figure 1, we are now at the "Consolidation" of our implementation. The following are some key areas that we feel need to be addressed in the near future:

- *Consolidation of coverage of existing skills* – Coverage of several CDIO skills (e.g. systems thinking, critical thinking and sustainable development) are somewhat "scattered" at the moment. We may also group related skills into the same assignment to provide a more holistic approach towards mastering these skills.
- *Enhance transferability of skills* – there needs to be a gradual progression in improved proficiency in the various CDIO skills acquired over the 3 years of study. We need to review our learning tasks to focus on enhancing transferability.
- *New Skills* – There are new skills that we had yet to integrate into the curriculum, e.g. sense-making, adaptive thinking, etc. These skills may not be so easy to integrate, and need greater use of wider range of pedagogic approaches. Faculty may also need more intensive training.

- *Resources* – Additional manpower may be needed for teaching of new skills, as well as new workspaces that cater for smaller class size interaction.

Perhaps the most important challenge of all is to sustain the revamp effort. It has been cautioned that "many have encountered significant problems around 5–10 years after the graduation of their first cohort of students. Most experience a gradual course-by-course 'drift' back to a more traditional curriculum [17]". In its report *Innovation with Impact*, the ASEE noted that [18]:

> "If the 'grand challenge' for engineering education is '*How will we teach and how will our students learn all that is needed to tackle the challenges of today and tomorrow?'* then the issue is *not* simply a need for more educational innovations. The issue is a need for more educational innovations that have a *significant impact* on student learning and performance (p.5)"

The report urged that a culture of educational innovation be created so as to sustain educational innovations with significant impact; and it provided several recommendations towards this end. We see parallels between many of these recommendations and the CDIO Standards as we went through the self-evaluation process. Of particular note is the call for continual improvement to make engineering programs more engaging and relevant; by conducting periodic self-assessment to measure progress in curriculum revamp implementation. Another is the need for increasing awareness of proven principles and effective practices of teaching and learning among faculty, as well as providing career-long professional development to enhance faculty competence. Although we had introduced faculty professional development via the T&L Unit as mentioned earlier, we felt that developing faculty CDIO capability is the key to impactful innovations. We aim to make the process more structured and systematic by integrating our CDIO self-evaluation process into the institution's quality management system. Details of this had been covered in a separate paper for this Conference [19].

CONCLUSIONS

Our journey to revamp the DCHE curriculum using CDIO framework is a rich and rewarding experience. It has been both timely and appropriate to meet the changing demands of chemical engineering education that have been taking place over the last ten years. Our effort seems to have been successful so far, based on survey feedback received from both students and graduates. Furthermore, we have achieved this without incurring additional curriculum hours as well as retaining all the fundamental chemical engineering technical content knowledge. We had overcome key challenges among faculty acceptance and also identified several factors deemed critical for the success of this program. All of these had a common denominator: the *human dimension*. Specifically, this entailed the importance of leadership support, role of early adopters and education advisors, changing of faculty mindset and managing student expectations.

However, the journey is far from over. As noted above, there are still a number of significant changes that we plan to make to the curriculum over the next few years. There are new challenges that will inevitably come up that need to be addressed. The approach outlined in this paper will continue to form the foundation on which our curriculum revamp will be based.

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BIOGRAPHICAL INFORMATION

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