USING CDIO TO REVAMP THE CHEMICAL ENGINEERING CURRICULUM

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ABSTRACT

This paper discusses how the CDIO framework is used to reengineer a curriculum revamp for the Diploma in Chemical Engineering at Singapore Polytechnic. A brief introduction to the "traditional" way chemical engineering program is being taught is presented followed by a discussion on rising importance of including general transferable skills and chemical product design skills in the educational landscape and its impact on the chemical engineering curriculum. The shortcoming of the present course in its coverage in terms of the requirements of CDIO Standards and Syllabus were discussed. The approach taken to revamp the curriculum, which resulted in a new course structure, is presented, followed by brief descriptions on work done for selected modules, namely *Introduction to Chemical Engineering*, *Plant Design Project*, *Chemical Product Design* and *Chemical Reaction Engineering*. Key learning points from the revamp exercise were discussed, how some of the challenges were being overcome, followed by discussion on plans formulated to continue the curriculum revamping effort. Lastly an overview was given on how recent development on education for sustainable development as well as the integration of process and product designs can affect the education of chemical engineers, and how the CDIO framework can be utilized to continue to drive the reform in chemical engineering education.

KEYWORDS

Chemical engineering, course structure, chemical product design, process plant design

CHEMICAL ENGINEERING EDUCATION IN THE POLYTECHNIC

A key objective of a chemical engineering education is to synthesize the many subjects studied into the design of a system, component, process, or experiment. The hallmark of traditional chemical engineering education in the universities is that of chemical process design, often with a requirement that students complete a plant design project in their final year of study.

Teaching of chemical engineering in the polytechnic closely mirrored that of degree programs in universities, albeit in a simplified version pegged to the diploma level, which is a 3-year program. The various chemical engineering disciplines are taught in a modular fashion. A notable feature of polytechnic education is probably the more extensive hands-on experience of operating various pilot plants, large and small, compared to the universities. Other than that, polytechnic graduates can pretty much expect to deal with familiar topics but at a more conceptual level when joining the university.

Much like the university, chemical engineering education in the polytechnic also include chemical process design, whereby students are required to complete a chemical plant design project based on a given problem statement to produce a given commodity chemical. Students often work in team to come up with a process design to achieve the required production. Students typically carried out literature survey of available processes and upon selecting one, proceeded to carried out computer simulation for all the process flow streams and the equipment contained in the selected process, complete with a environmental and safety analysis of the design.

The traditional focus on chemical process design, coupled with a largely modular course structure, meant that the polytechnic's chemical engineering curriculum is delivered via various modules each addressing a particular discipline of chemical engineering, relying on the integrative nature of plant design project to bring together the various concepts learnt. The obvious downside is that students tend to compartmentalize their learning, and are often unable to utilize the relevant disciplinary knowledge in solving their plant design problem. It was also observed that students tend to rely on trial-and-error in computer simulation to give them a "design" without much interpretation of the simulation results. It is further noted that chemical engineers typically carry out simulation and equipment design work for an individual piece of equipment as part of plant modification or upgrading work (for example, debottlenecking). It is very rare for diploma-level graduate to ever be involved in intensive plant-wide design work.

CHANGES IN CHEMICAL ENGINEERING EDUCATIONAL LANDSCAPE

Two major changes in the education of chemical engineers had taken place over the last couple of years: (1) Emphasis on General Transferable Skills; and (2) Emergence of Chemical Product Design.

Chemical product design is beginning to emerge as an important discipline in chemical engineering. This is largely the result of changing competitive landscape in the chemical processing industry. Today's chemical industries have been facing dramatic social, economic and technical challenges, on a global and local scale. Globalization, for example, has brought about rapid changes in businesses and technologies, resulting in organizations making deep and rapid changes in the scope of their activities and the strategies adopted to remain profitable and achieve sustainable growth. With advances made in information technology, green chemistry and nanotechnology, etc, many of the chemical products of today and tomorrow do not have much in common with those of twenty years ago. Production of commodity chemicals had been overtaken by high value-added specialty chemicals. The portfolio of skills and technical knowledge required by chemical engineers, as well as the working environment, has therefore changed tremendously, which increasingly focused on soft skills (or 'higher order' skills or general transferable skills) in teamwork, communication, appreciation of multi-cultural diversity, etc. Like those in other engineering disciplines, there was a growing dissatisfaction among the chemical industries with chemical engineering education. Much of the criticisms had been levelled at the inadequacy of soft skills among chemical engineers or chemical engineering graduates. A concise review of this had been presented by the author [1].

In their seminal paper, Moggridge and Cussler emphasised the need for chemical product design and elaborated on the expanded role of chemical engineers, highlighting the necessity for them to work in teams in a joint effort of product design through participation in the whole enterprise from conception to manufacture [2]. Chemical product engineering is now being cited as the next paradigm for chemical engineering, and an increasing number of universities now offered chemical product engineering-related courses [3].

CDIO AND DIPLOMA IN CHEMICAL ENGINEERING CURRICULUM REVAMP

The above change drivers served as the impetus for revamping the chemical engineering curriculum. In this regard, the CDIO framework [4] fits in well with the strategic intent of the revamp, which is to introduce students to skills in conceiving, designing, implementing and operating chemical products, systems or services, in a manner that integrates the various chemical engineering disciplines along with other general transferable skills.

A study of the chemical engineering curriculum coverage vis-à-vis the CDIO Standards and Syllabus was undertaken. Overall, at the course level, the various CDIO skills such as teamwork, communication, plus broad aspects of personal skills and attitudes, as well as engineering reasoning and problem solving, experimentation and knowledge discovery are loosely covered in various modules. More importantly, the study revealed several areas where the curriculum is lacking, namely a module on introduction to engineering (CDIO Standard 4), and overall skills in conceiving, designing, implementing and operating an engineering product or system (CDIO Syllabus Part 4). Although some aspects of these skills are practiced in the execution of a student final year project, there is no systematic framework that guides this process and as a result the approach varied considerably from project to project depending on the supervisor. As such, the execution of final year project needs to be fine-tuned to enhance features of the so-called Design-Build Experience (DBE) in CDIO parlance. Opportunities also need to be created to introduce DBE to students at an early stage in their study rather than just at the last phase in the form of final year project (CDIO Standard 5). Also needing to address are skills in system thinking and appreciation of ethics in practice of chemical engineering.

The study also showed that more can be done to integrate the various core chemical engineering modules taught in a modular manner (CDIO Standard 3). The various CDIO skills should be embedded into the core chemical engineering modules and learnt alongside the technical subjects (CDIO Standard 7). These skills can be enhanced and reinforced in the laboratory activities by re-designing the experiments to be more engaging and enriching for the students (CDIO Standard 8).

There is also a need to provide new workspaces to cultivate the developments of skills in conceiving, designing, implementing and operating a chemical product or system (CDIO Standard 6). Although the curriculum is rich with hands-on opportunities for students, these activities all centred around the operation of pilot plants. When it comes to final year project work, students have to make do with existing facilities in the existing laboratories, which often lack both privacy as well as proper facilities such as storage space, printing and communication equipment. Insufficient attention had been paid in the past to such needs. Lastly, from the study it is also clear that lecturer competency need to be build up (CDIO Standards 9, 10 and 11), especially in chemical product design.

From the study, it is obvious that new modules need to be introduced. To make room for the introduction of new modules in an already-crowded curriculum, existing modules were revised, merged or otherwise removed. Overlapping contents were removed, while similar concepts were trimmed and converted to independent learning. The outcome of the curriculum revamp is the modified course structure for teaching chemical engineering, which is shown in Figure 1.

Next step is the study to review how the various CDIO skills can be infused into the curriculum. In this regards, the course management team worked closely with the polytechnic's CDIO Working Committee, to develop an appropriate CDIO Syllabus suitable for diploma-level students. Subsequently, a CDIO Syllabus for chemical engineering was produced based on the original CDIO template [5]. Next, the team proceeded with the selection of three CDIO skills (namely, teamwork, communication, and personal skills and attitudes) for infusion into the DCHE curriculum. A set of underpinning knowledge for these three skills suitable for the polytechnic's context were developed. A mass training for all academic staff was conducted, followed by a focused training on the underpinning knowledge for a group of trainers. A detailed gap analysis was then carried out to identify shortfalls in the coverage of these three skills in the existing curriculum.

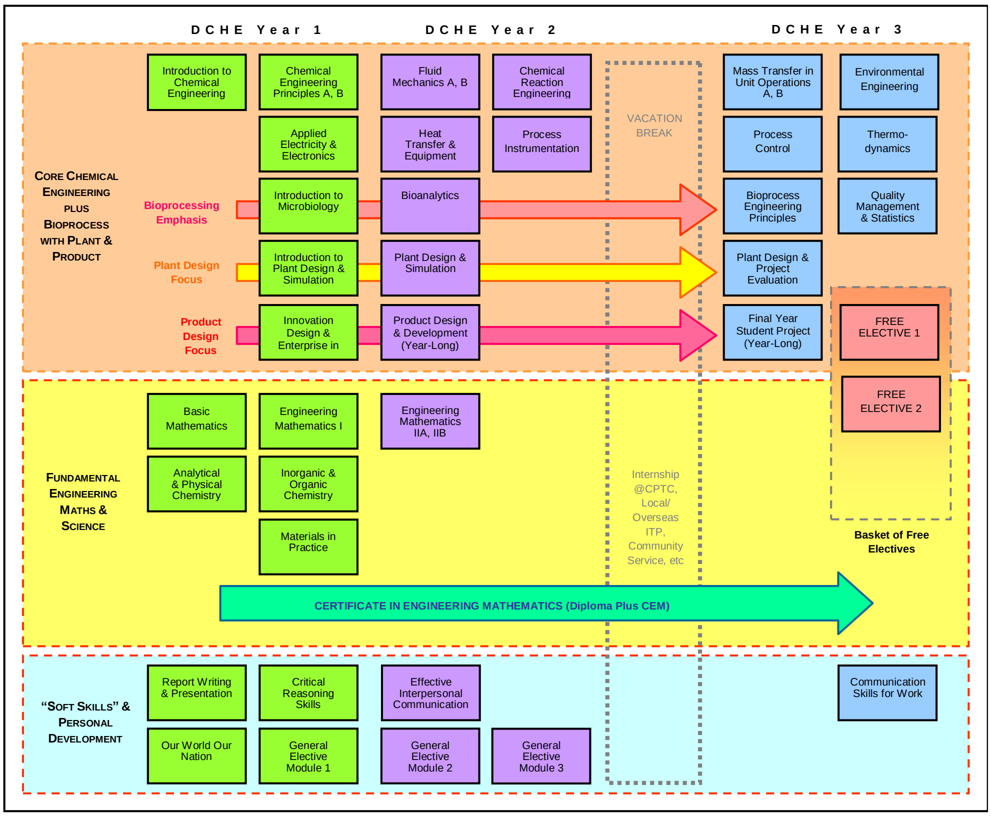

Figure 1. Revised Chemical Engineering Course Structure

A pilot module, representing a core chemical engineering discipline with laboratory experiments, was then selected for trial application. The team recognised that the laboratory experiments, compared to lectures and tutorials, are rich in hands-on experience, thus can best be leveraged to provide the greatest opportunity and largest context on which infusion of CDIO skills can be initiated. Along with the integration of CDIO skills, the team also reviewed ways to more closely integrate the various chemical engineering disciplines while maintaining the modular design of the curriculum.

Introduction to Chemical Engineering

This is a new Year-1 module, introduced to familiarise students with the chemical engineering profession, chemical industry, plus roles and responsibilities of a chemical engineer. The module was features activities designed to offer appreciation to the kind of job that a typical chemical engineer does. The module also introduces students to DBE project early in their course of study, by challenging them to come up with a simple product design and evaluate its performance. Students were also exposed to the requirements of the three selected CDIO skills of teamwork, communication, and personal skills and attitudes. Details of this work will be presented in a separate paper [6].

Chemical Product Design

The introduction of this Year-2 module serves to provide the much needed extra dimension in chemical engineering education to move it away from just chemical process design. For this module, the team decided to adopt the approach introduced by Moggridge and Cussler [7] as it had much in common with Part 4 of the CDIO Syllabus. The authors outlined a simplified 4-step product design procedure centred around the concepts of 'needs', 'ideas', 'selection', and 'manufacture' which is widely used in business development and manufacturing engineering. The development work for this module will be the subject of a future paper.

Chemical Process Design via Plant Design Project

From the earlier discussion on chemical process design, it is clear that this does not satisfy the Conceive, Implement and Operate concepts of CDIO, as all the students experienced was computer simulation exercises. The revamp of the teaching of chemical process design therefore centres on how to make the plant design exercise more meaningful to our students, other than satisfying the needs of those who intended to further their studies in chemical engineering. To this end, the team decided to break-up the plant design project into "bite sizes", spreading it over the entire duration of the 3-year program. This begins with an appreciation of process flowsheeting in Year-1 and exposure to process simulation. Plant design and simulation was subsequently integrated into various modules in Year-2 and Year-3, rounding of the exercise with a project in the last stage of study in Year-3.

Chemical Reaction Engineering: Integration of CDIO Skills

Lastly, we focus on the revamp of *Chemical Reaction Engineering* to be the pilot module to showcase how various CDIO skills can be infused into a highly technical core chemical engineering module. Extensive research has shown that students learn best when they perceived a clear need to know the material being taught [8]. It is also clear that the best opportunity lies not in the classroom but in the laboratory, where students are to work in teams. Technical know-how and competences in soft skills are all integrated into the same learning environment, as competences are considered to be context-dependent (i.e. as contextualized competences) and should be learned and assessed in the technical context [9]. As such, the teaching of communication should therefore be embedded in, and inseparable from, students' application of technical knowledge. The laboratory activities for this module are therefore revised using real-life work scenario so that students can experience the needs to master the various CDIO soft skills. Emphasis is placed on the three selected CDIO skills of teamwork, communication, and personal skills and attitudes. Details of the work done on this area are covered elsewhere [10].

KEY LEARNING POINTS FROM THE CURRICULUM REVAMP EXERCISE

Several important lessons can be learnt from the curriculum revamp exercise.

Without a doubt, the single biggest challenge to the revamp effort is that of staff buy-in. The CDIO Initiative must not be seen as another management fad that will come and go; something lecturers pay lip service to without putting in serious effort to carry out any meaningful changes in the modules. Continued effort is necessary to convinced everyone that the current revamp is an ongoing process in the spirit of continuous improvement, and the CDIO Initiative is no more than a framework that fits the broader objective of the revamp. Since it is an internationally-led effort by reputable universities, its sustainability should be assured. To encourage buy-in, lecturers are also encouraged to use the CDIO Initiative as the platform to conduct educational research, in line with the career progression system in the polytechnic. Management support is also frequently sought to sponsor deserving lecturers to attend CDIO conferences or collaborators' meetings overseas.

Also, in initiating the curriculum review, it is clear from the onset that improvements are required in the way many module syllabi are written. Based on Bloom's taxonomy, many existing syllabi were mainly written at knowledge and comprehension level rather than more performance-outcome-based. Many module coordinators are relatively new and do not fully grasp the concept of outcome-based education (OBE) and hence had difficulty with writing syllabi in terms of learning outcomes.

A related issue is the preparation of assessments. There is an apparent disconnection between module syllabi, choice of assessment methods and what is being assessed. Often assessments are prepared largely independent of what is being written in the syllabi. Students are often tested on knowledge and understanding, rather than competency to perform a given task. This is one big area where one can expect most lecturers will have problems in. Difficulty also existed in assessment of soft skills, as lecturers tend to focus only on the technical content of students' output. Part of the reason was the lack of time, another being the lecturers themselves do not know "what to look for". Needless to say this is the most important area to address, as the correct learning objectives are what drive the curriculum design and the assessment methodology. More staff development workshop may be needed to address this issue.

On the effort at integrating the curriculum, one of the most important challenges faced is that many lecturers tend to compartmentalize their own teachings; hence it is not entire surprising that students also compartmentalized their learning! One contributing factor to this is the modular nature of the course structure and assessment system. A module's "success" is measured largely by the passing rate of students taking that particular module, scoring on questions related to that module. Knowledge of another module is necessarily assessed in the other module's own assessment system. The other is the lack of communication between the lecturers themselves. It is also the tendency of lecturers to cover as many topics as possible. In the lecturer's mind, all current topics are individually self-classified as essential. If anything is to be done is to extend them! Getting individual lecturers to reduce the module content to include some aspects of integration with other topics posed a big challenge.

Curriculum integration can only be effectively achieved if each lecturer is aware of what the other lecturers are teaching. The practice of rotating module teaching using different lecturers after a few semesters will help facilitate common understanding between them. Getting each lecturer to include several questions relating the concepts in the module that they are teaching to topics beyond the module also serves to provide much-needed linkages between modules. For example, a tutorial on the topic of heat exchanger operation can include a question of temperature measurement and control such as sensor selection, serving to illustrate how the concepts learnt on the module *Process Instrumentation* can be in the module *Heat Transfer and Equipment*.

And as expected, gap analysis turned out to be a time-consuming process, and several rounds of iterations are required before an acceptable outcome is attained. The results from the gap analysis showed varied level of understanding among the lecturers on what needs to be done to infuse CDIO skills into the curriculum, despite the workshops and briefings. Some module coordinators appear more or less to get it, but others apparently do not. For instance, several lecturers apparently thought that one had achieved infusion of teamwork in their respective modules, simply by dividing students to work in groups for their laboratory experiments. In another instance, a lecturer reported that students are taught time-management because the lecturer concerned had reminded them to submit their reports on time. Similarly, misconception among lecturers is also rather common on what constitute a DBE. Many are of the opinion that having students complete a final year project automatically ‘qualifies’ the curriculum as meeting the CDIO ‘requirements’. It took significant effort to change these mindsets, via constant reminders and frequent briefing sessions. The successful implementation of the pilot module is often used to illustrate how the integration of general transferable skills into a core chemical engineering module can be achieved.

On the plus side, gap analysis also highlighted several good practices among lecturers in their individual effort to engage students in one way or another. Among other things, gap analysis revealed a wide variety of approaches for example radar chart, peer assessment, 2-tier Q&A, etc. All in all, the efforts spent on the gap analysis exercise are very worthwhile, as it functions, for the first time, as a mechanism that forces each lecturer to seriously think through the learning objectives of the respective module and the laboratory exercises or assignments that contained in the module. An obvious advantage is that it highlights some laboratory experiments that merely require students to verify already known theories. To a large extent, most laboratory experiments, though not specifically embedding any general transferable skills, had now done away with theory-proving activities.

Lastly, though not least important, is that of staff competency. Two areas are of concern here: one concerns competency in general transferable skills and one concerns competency in chemical product design. The former posed some problems initially in terms on the perceived ambiguity among lecturers on how, not being ‘experts’ in the areas of soft skills, especially that of system thinking, can they effectively design activities involving these skills and assessing them. The use of a pilot module of *Chemical Reaction Engineering* as briefly explained above followed by sharing of key learning points through workshops had served to allay the fears of these lecturers.

However, unfamiliarity with techniques of chemical product design is arguably likely to cause anxiety among lecturers. The current pool of lecturers is being trained in ‘classical’ chemical engineering which lacked practical experience in chemical product design and development. The teaching of chemical product design using chemical engineering principles is a relatively new concept for majority of chemical engineers. This is because these products, which include performance chemicals, pharmaceuticals, formulated products such as household, beauty or personal care products, and processed foods; have historically been the domain of chemists, material scientists and food technologists while chemical engineers focused on manufacturing processes [11]. Although preliminary training in this area had been provided, it will require some time before lecturers are comfortable with these skills and are able to use them fluently in their teachings.

THE PATH FORWARD

We are just at the beginning of the curriculum revamp, whereby the revised curriculum with CDIO skills integrated into selected modules being rolled out in April 2008. The team took part in a campus-wide evaluation of Singapore Polytechnic’s CDIO implementation effort, and engaged students as co-participants in providing feedback to the team on the effectiveness of the curriculum revamp effort. Details of the methodology employed are covered elsewhere [12]. At the time of this paper, we had obtained feedback from students taking the modules *Introduction to Chemical Engineering* and *Chemical Reaction Engineering*. While the work done for these modules are discussed elsewhere [6], [10]; suffice to say that the student feedback had been encouraging, and they had served as important pointers to guide the revamp and design of other modules to include the CDIO skills. We will undoubtedly continue to monitor student performance and obtain their feedback as we moved along.

At the micro level, more chemical engineering core modules will be targeted for revamp. Much can be done to the infusion of the first 3 skills (teamwork, communication, and personal skills and attitudes) into the various core modules other than *Chemical Reaction Engineering*. For the next phase of the implementation plan, several other modules had been selected for the continued infusion of these 3 skills. Starting with Year-1, the importance of these skills will be introduced to students via carefully-designed laboratory experiments. These will then be further reinforced in Year-2 modules with the aim that by Year-3, students will be able to utilize these skills in their laboratory works.

Additional CDIO skills had been selected for integration into the modules. These are Experimentation & Knowledge Discovery, System Thinking, and Professional Skills and Attitudes. Additional modules had been identified for the inclusion of these skills in the curriculum. The team will continue to re-design more laboratory practicals using various task scenarios for students. As chemical engineering education is very broad-based in nature, both in the polytechnic and university undergraduate level, introducing scenario-based activities for the 5 experiments in one module does not necessarily cover all possible workplace situations. Furthermore, it has been shown that such approach did serve to provide students with some degree of appreciation of their job scope and environment. With other modules providing somewhat different scenarios, it is hoped to cover as many different workplace scenarios as possible for our students.

More modules will be required to include cross-module integration. The previous integration effort largely centres on introducing additional questions on topics other than the module in question into the laboratory exercises, typically in the report submission section. With the revised approach to plant design project, it can be expected that more integration between the core chemical engineering modules will take place via design and simulation assignments. These plant design and simulation assignments are also fertile ground for the reinforcements of core CDIO skills of teamwork and communication. More can be also done to also cross-link core chemical engineering principles into lectures and tutorials, as well as assignments or case studies. In the pipeline is a proposed integrated assignment that spanned several modules for example *Fluid Mechanics*, *Process Instrumentation*, and *Heat Transfer and Equipment*. Such an approach may also be applied for those modules without laboratory practicals.

In April 2008, a new module on chemical product design had just been introduced into the Year-2 curriculum. Already in progress at the time of this paper is work to forward integrate chemical product design with the student final year project. Traditionally final year project in chemical engineering are largely proposed by lecturers. When opportunities arise to collaborate with external research institutes, these initiatives (called industry-sponsored projects) are incorporated as final year projects as well. More recently, the team introduced the so-called student-initiated projects, whereby students can suggest suitable topics where they would like to work on. This has limited success as students in general lacked the skills to conceive meaningful, executable projects. With the introduction of the new module on chemical product design, it is hoped that more projects can be initiated by students.

However, it must be recognized that not all ideas may proved to be feasible or implementable. As such, a fall measure is needed and this means lecturers are required to continue to propose projects for students without a workable proposal when they entered Year 3. Also, there remains the need to remain in touch and in support of the chemical industry by continuing to work on industry-sponsored projects. By its nature, these projects usually lack the CDIO components of “conceive” and/or “design” components as the project objectives had been largely determined by the company sponsoring the projects. Often students are enlisted to help in conducting experiments on behalf of post-graduate students or company R&D personnel. The intended learning outcomes are different for different type of projects. In industry-sponsored projects, industry partners obviously had a different attitudes and expectations toward project outcomes compared to our own lecturers. Similarly, post-graduates or doctorate students, with a more focused approach and time on hand, not to mention a dissertation at stake, tend to be more participative in the project work compared to our own lecturers. As such, the work remaining to be done is to develop separate assessment criteria for the different categories of final year projects. It is important that students are assessed based on different criteria relevant to the nature of the project.

As lecturers become more familiar with chemical product design, the team can also move into the study of its integration with the 'traditional' chemical process design. In fact, Amundson has long highlighted the need to integrate product design with process design [13], arguing that chemical engineering will serve as the "interfacial discipline" of the future, bridging science and engineering in the multi-disciplinary environments where new technologies will be brought into being.

At the macro level, the team will be looking at the setting up of a CDIO workspace conducive for students to carry out their final year projects with DBE. The challenge here centred on the limited resources available in campus. Although in general no new workspaces are needed for the integration of various general transferable skills, there is a real need for visible workspaces for new pilot plants to cater to the needs of new and emerging disciplines such as biofuels and clean energy, and pharmaceutical and bioprocessing. Increased focus these areas had already placed a demand on the available laboratory space, and thus new location need to be sourced for the provision of the envisioned CDIO workspace.

For the longer term, the team will continue to study the changes that is affecting the chemical engineering industry in general, and in the education of chemical engineers in particular vis-à-vis the ongoing reform in engineering education. Already gaining accelerated attention is education on sustainable development. The chemical engineering profession had staked its position to support sustainable development following the Melbourne Communiqué by the Institution of Chemical Engineers U.K. in 2001. Similarly, the U.S. National Research Council (NRC) has identified sustainability education as one of the eight Grand Challenges confronting the chemical industry. It is therefore inevitable that 'next phase' for the Diploma in Chemical Engineering curriculum revamp to focus on the integration of sustainable development in its modules.

With all these development, the role of chemical engineers will no doubt take on yet another new dimension. The introduction of chemical product design in the DCHE curriculum is timely as product design has been identified as one of the engineering tools that form the architecture for sustainable development [14]. Grossmann emphasized that chemical engineers need to adopt broader approaches to the life cycle assessment of products and processes in order to predict more accurately their long-term sustainability [15]. With its focus of life-cycle analysis, the team believed that the CDIO approach, with its Conceive-Design-Implement-Operate framework, lends itself readily to incorporate the requirement of sustainable development into its chemical engineering curriculum. Hence the team is confident that its graduates will be able to play a proactive role in the development of new products that meet the requirement of sustainability.

CONCLUSION

The Diploma in Chemical Engineering is indeed in turbulent yet exciting times. With the multi-prong approach adopted, the CDIO framework will serve the course well into the foreseeable future with the ongoing curriculum redesign effort. The lessons learnt from the initial phase of curriculum revamp are useful to help fine-tune subsequent change effort. Given all the prevalent developments, there is no doubt that our graduates need to be equipped with the necessary skills to handle the challenges that confront the chemical engineering profession. Indeed, a recent review by Cobb et al concluded that the description of what really is a chemical engineering continues to evolve – and that chemical engineers must be life-long learners [16]. The outcome of the revamp will not be known until the first cohort of students graduate from the course (and this will only happen after the academic year 2010/2011) and gain employment in the chemical and allied industries. The team will prepare an extensive employer survey to find out if the curriculum revamp had met its intended objectives.

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