SUPPLEMENTING CAPSTONE PROJECTS: CURRICULUM INTEGRATION USING PROCESS INSTRUMENTATION & CONTROL

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ABSTRACT

The Diploma in Chemical Engineering (DCHE) course of Singapore Polytechnic (SP) adopted the CDIO framework as the basis for its curriculum in 2007. Since adoption, specific CDIO skills have been successfully integrated in various core modules in the 3-year diploma program. A range of Interpersonal Skills, such as teamwork and communication, and Personal & Professional Skills are now established curriculum components.

This paper focuses on the efforts taken to enhance curriculum integration in the chemical engineering curriculum using a core module entitled *Process Instrumentation & Control* (*PI&C*) taught to Year 3 students. It firstly presents an overview of the integration approaches used; and some limitations of existing approaches, including the *Final Year Project* and *Plant Design Project*. It then shares how we redesign the P&IC module, which is widely perceived to be difficult, to become more interesting for students through a well-integrated curriculum.

Secondly, it presents our experience in designing real-world learning tasks that integrate across modules, CDIO skills and within domain knowledge areas from multiple disciplines. Findings from our evaluation are summarized and certain challenges identified. The paper concludes with a reflection on CDIO teaching experiences by the first author, who is relatively new to the teaching profession, as well as some recommendations for future action.

NOTE: 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”.

KEYWORDS

Curriculum integration, chemical engineering, process instrumentation and control

INTRODUCTION

The Diploma in Chemical Engineering (DCHE) in Singapore Polytechnic (SP) adopted CDIO as the organizing education framework for a major curriculum redesign initiative in 2007. Various CDIO skills such as teamwork and communication, personal skills and attitudes (e.g. critical and creative thinking, managing learning, holding multiple perspectives, etc.) have been integrated into the curriculum. This paper covers the effort by the DCHE Course Management Team (CMT) to integrate its 3-year curriculum both in terms of technical contents and CDIO skills, consistent with CDIO Standard 3 ”Integrated Curriculum” using a Year 3 core module entitled *Process Instrumentation and Control*.

THE NEED FOR CURRICULUM INTEGRATION

The need for curriculum integration is best summed up by Sheppard et al [1] who noted that: “Although engineering education is strong on imparting some kind of knowledge, it is not very effective in preparing students to integrate their knowledge, skills and identity as developing professionals … The tradition of putting theory before practice and the effort to cover technical knowledge comprehensively allow little opportunity for students to have the kind of deep learning experiences that mirror professional practice and problem solving.” The authors further noted the traditional engineering education model “with its attendant deductive teaching strategies, structured problems, demonstrations, and assessments of student learning does not reflect what the significant and compelling body of research on learning suggests about how students learn and develop and how experts are formed.” Integrating the curriculum can be done in a number of ways (see Fogarty, [2]); and as Drake and Reid [3] point out: “Research has consistently shown that students in integrated programs demonstrate academic performance equal to, or better than, students in discipline-based programs. In addition, students are more engaged in school, and less prone to attendance and behaviour problems.”

CURRICULUM INTEGRATION IN CHEMICAL ENGINEERING

We have used the following approaches to integrate our curriculum:

(1) Integration of technical knowledge across different disciplines, e.g. mathematics and sciences (e.g. chemistry and biology) in chemical engineering, mostly in Year 1 and Year 2
(2) Integration via capstone projects, which in our context, consists of the *Final Year Project* (*FYP*) and the *Plant Design Project* (*PDP*), both in Year 3
(3) Integration of CDIO skills (e.g. teamwork, communication, critical thinking, etc) in selected core modules across all three years
(4) Integration of C-D-I-O skills (skills in conceiving, designing, implementing, and operating an engineering product, process or system) across all three years

Prior to CDIO, we had relied on approach (2) as the *de facto* approach to curriculum integration, assuming that, by completing these projects, our students will naturally come to realize the importance of bringing together and utilizing the knowledge they acquired over the years to complete a given task.

With the adoption of CDIO, we initially focused our attention in curriculum integration using approaches (3) and (4). These efforts had been described elsewhere [4], [5]. Suffice to say that we felt that approach (3), while successfully implemented in the curriculum through various laboratory activities in several core modules, is still somewhat limited in terms of its effectiveness the subject matter in the core module is still the dominant focus. Similarly, approach (4), which addressed the challenge in chemical engineering education in introducing product design into a traditionally process-oriented curriculum, remains inadequate in fostering the desired integration, as this tends to focus on the specific skills of C-D-I-O in chemical product design.

The main focus of this paper is to share our experience post review of our integration efforts, and a new initiative taken to address the shortcomings identified. It will be made apparent that part of the problem is a result of our modular curriculum approach, which relies largely on the capstone project to realize the goal of curriculum integration, where students are often told – when they are in Year 1 and Year 2 – that "these concepts will become useful to you later when you do your final year project." Froyd and Ohland [6] had criticised this type of modular teaching, noting that: "Questions have been repeatedly raised about whether neatly compartmentalized courses can provide learning activities that stimulate, encourage, and enable students to structure their knowledge across course and disciplinary boundaries". Humphreys et al [7] summed up the attitude well, when they noted:

> "It is taken for granted, apparently, that in time students will see for themselves how things fit together. Unfortunately, the reality of the situation is that they tend to learn what we teach. If we teach connectedness and integration, they learn that. If we teach separation and discontinuity, that is what they learn. To suppose otherwise would be incongruous.(p.xi)".

The following sub-sections provide a brief discussion on the limitations of the two projects (*FYP* and *PDP*) that lead to the need to reinforce the integration efforts using other core modules.

Curriculum Integration via Plant Design Project

Invariably, most chemical engineering programs worldwide require students to complete a process plant design project (i.e. *PDP* in our context) which serve as the "capstone" project for the discipline. In the *PDP*, students working in groups are required to carry out a conceptual design (using computer modelling and simulation) of a chemical plant to produce a given product of specified purity and production rate. A potential pedagogical drawback for this is that the physical chemical plant is never actually built! In this sense a "capstone" project in chemical engineering is quite different from similarly-named projects for other disciplines, e.g. mechanical engineering. It is therefore possible for students to successfully construct and use computer models without really understanding the physical phenomena within each unit operations that comprise the complete process plant [8]. Indeed, often we find students focusing too much on getting the simulation program to converge, by trying different process parameters instead of interpreting the error messages to understand why the program failed to converge in the first place.

Also, what is really lacking in this approach is the lack of realism of chemical engineering practice. Some institutions tried to inject more realism into such projects by requiring students to work on real-world process design, some with industrial partners. However, at the diploma-level, due to time constraint and knowledge level of the students, the project is scoped such that there would not be sufficient depth to carry out the sort of rigorous analysis as in the university degree programs. We did not engage industry partners although the project brief is still based on real-world chemical plants.

Curriculum Integration via Final Year Project

The student *Final Year Project* (*FYP*) is another platform towards curriculum integration. The *FYP* is closer to the CDIO Design-Implement Experience (Standard 5) in terms of offering hands-on opportunity for students with a product and/or process as the deliverable. Approach (4) mentioned earlier is intended to supplement the students' C-D-I-O skills in their *FYP*; and do not contribute to the integration of technical knowledge per se. Henceforth, we observed that relying on *FYPs* to achieve the objectives of curriculum integration is inadequate, and over the years had noted some lingering problems with this approach:

(1) As projects can vary greatly (e.g., feasibility study, applied research and experimentation, pilot-testing, process plant design and optimization), this poses real challenges in ensuring equitable learning outcomes for all students.
(2) Related to the above, as a project can last a few years, with each student cohort working on individual phases of C-D-I-O towards final completion, the same cohort of students rarely follows through a project from inception to completion.
(3) Depending on the nature of the projects, not all learning outcomes can be covered within the given project. For example, a project on feasibility study on certain species of algae to produce biofuels, will not engage students directly in troubleshooting a fixed-bed chemical reactor typical in an oil refinery.
(4) Most importantly, students still face difficulty in synthesizing the diversity of knowledge needed to tackle the challenges in the *FYP*.

CURRICULUM INTEGRATION USING *PROCESS INSTRUMENTATION & CONTROL*

When we were re-designing our learning activities for approach (3) we noted a pattern which led to an opportunity for improving our curriculum. Specifically, we noted that topics in the module *Process Instrumentation and Control* (*PI&C*), currently taught to Year 3 students, can serve as key organising concepts integrating other core chemical engineering principles. We found that there are many activities, even in Year 1, that lend themselves to the introduction of process control principles. This continues into other modules in Year 2 and Year 3, as shown in Figure 1. In this way we introduced concepts of process control to students straight away in Year 1, slowly building up their knowledge and application in Year 2. Detailed and theoretical concepts of process control are "delayed" to Year 3 teaching.

We also see saw leverage in using *PI&C* as a module to supplement curriculum integration. The topics had typically been regarded by students as challenging and difficult with abstract concepts distant from real life situations. The "traditional" approach is for students to apply the process control principles in *PDP*, and where appropriate, in *FYP*. Due to the uniqueness of chemical processes, teachings of process control differs significantly from that of electrical or mechanical engineers [9]. In fact, process control has often stood out in the chemical engineering curriculum as a necessary topic that is oddly disconnected from the rest of the curriculum, leading to some authors arguing for a more active and experiential learning approach [10].

With this insight we re-designed the existing *PI&C* practicals to serve the dual purpose of firstly strengthening curriculum integration and secondly making learning the module more meaningful. As an "integrative" module, the re-designed activities now connect more directly to the relevance of various topics in chemical engineering, instead of merely learning about concepts and principles of various control theories and algorithms. We expect students to be able to integrate technical and soft skills, relate them to other modules and to solve real-world problems. Most importantly, we also wanted to know how these practical activities can potentially benefit them as future chemical engineers.

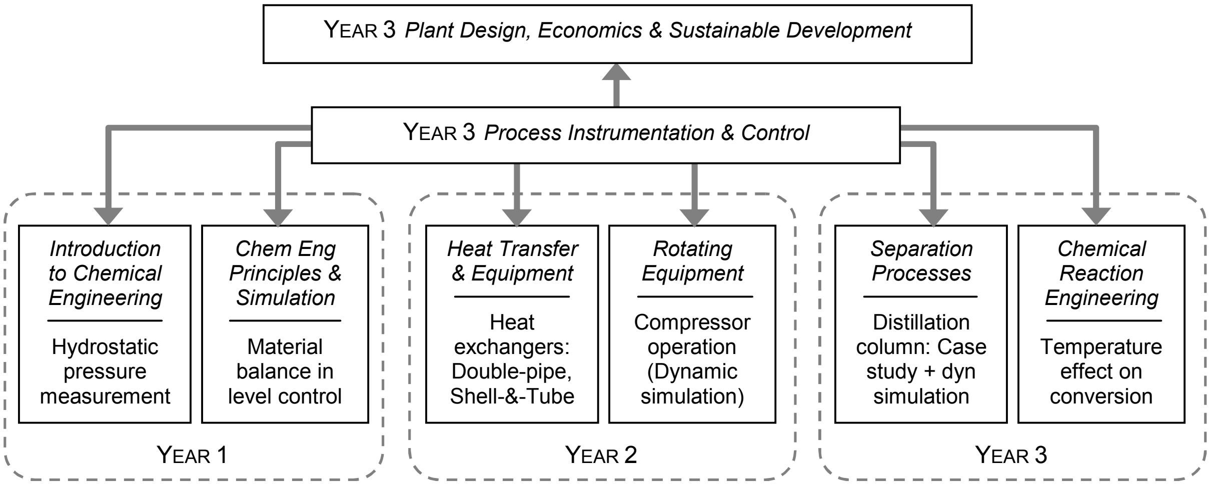

Figure 1. Presence of *Process Instrumentation and Control* concepts across core modules

We hope the sections below will be beneficial for any faculty facing similar challenges in teaching process instrumentation and control in chemical engineering.

APPRAISAL OF LEARNING OUTCOMES ACHIEVED

For our initial effort we revised two of the existing five laboratory activities for *PI&C*, creating real-world scenarios for future work as a chemical engineer. Students have to work in teams to solve simulated work problems requiring one to use knowledge in process control and other technical domains. Collaborative learning is promoted through pre-activity assessment that ascertain students' preparedness for the activity, utilising a series of structured questioning in which each team member must contribute collectively to the overall group marks.

In one activity we created a scenario whereby students had to assume the role of a newly promoted Chemical Engineer who was approached by the Plant Manager to urgently complete the task of tuning a new level controller of a wastewater treatment plant which was left uncompleted by his predecessor who had since left the company. Together with a team of process technicians (i.e. other students) the Chemical Engineer had to complete an originally five to six hour task within three hours. To carry out the work, the students need to use their technical knowledge on control theory, control algorithm and online controller techniques to design a suitable control strategy. In addition, they need to perform process line up, control valve stroke checking and finally starting up the plant in cold circulation. After some initial testing which yielded incomplete data (in view of serious time constraints) the students had to extrapolate, predict and use the available information to design an appropriate control strategy. They then implemented the strategy and evaluated it against actual plant performance.

This activity facilitated meeting desired learning outcomes which capstone projects like *PDPs* and *FYPs* could not consistently provide. Firstly, students were able to really try out the control strategy they designed. Unlike typical *PDPs* in which students generally were only required to determine the appropriate control algorithm and calculate the corresponding controller tuning parameter value from simulation results or tedious mathematical calculations (more often, this was only done for a selected section of the designed plant), this activity moved one step forward to allow students to integrate C-D-I-O skills, and more importantly, to evaluate the effectiveness of their work and finally to obtain an optimized result. The physical hands-on in unit start-up operation and shut down is also something that they were able to experience, unlike the *PDP* which is purely software simulation.

Secondly, by using a real-world scenario that requires engineers to handle urgent tasks within tight timelines, important CDIO skills were introduced. Students had to apply teamwork, communication and time management skills to complete the tasks within the time constraints. This could only be possible through proper planning and effective division of labor to bring out the synergy within the team.

Thirdly, students were given opportunity to evaluate the limitations in their initial design. The partial information obtained introduced elements of uncertainty which increases the challenges students faced to complete the task on time. They thus need to recognize possible sources of error and imperfections of the methods used; and understand that one cannot obtain the optimum result simply from the calculations alone. This gives them confidence to tackle problems, practice engineering judgment, manage uncertainty and incomplete information; all of which are inevitable in real-world engineering.

Fourthly, students were also being challenged at higher thinking levels when they were required to perform process troubleshooting based on the Five Steps of Process Troubleshooting technique [11]. Process fault scenarios were introduced whereby students are required to recognize the symptoms, hypothesize the cause of process faults, and propose actions and tests required to confirm their hypothesis.

Lastly, since this experiment involves the operation and control of a live process, the safety, health and environment aspects of plant operations were also being emphasized. Students were required to recognize and explain the various layers of protection in preventing the wastewater treatment tank from overflowing. In addition, students were also introduced to the concept of *using a safer substitute to minimize risk*. In the scenario, the wastewater treatment tank involves a neutralization process between a hazardous acid and alkali. Water was used as a suitable substitute in view of its non-hazardous nature and similar physical properties as compared to the acid and alkali mixture.

EVALUATION: ISSUES AND CHALLENGES

We carried out focus group discussions with selected students to first find out if *PDP* and *FYP* adequately helped them integrate knowledge gained over their course of study. We also wanted to know if the re-designed activities enhanced their understanding of their future job role as a chemical engineer. We also used a Reflection Journal (to be submitted individually) as a mean to evaluate if students are able to integrate the various technical and soft skills in the activities.

Confirming our expectation, students agreed that whether or not *FYP* is effective as an integrative capstone depends largely on the scope of each individual project. As for *PDP*, even though it was commonly agreed that it is a critical integrative capstone, many felt that there was too much emphasis on using the simulation software and insufficient guidance provided in seeing integrative links across modules. All students agreed that they were guilty of placing their emphasis of the project to get their simulations to converge by trial and error instead. They also admitted that integration efforts introduced in laboratory activities, notably written report assessment, are often circumvented by splitting up the work and complete their own sections of the report in silos; and that curriculum integration is still best achieved with actual plant experience.

From the focus group discussion, we identified three major challenges. The first challenge concerned the lack of guidance provided to them when performing the lab activities, which may have limited the effectiveness of achieving the intended integrative outcomes. Having been students ourselves, we acknowledge that at pre-employment level the students' plant experience is limited – hence expecting them to visualize a process plant at macro-level; linking problems and formulate solutions across multi-disciplines of chemical engineering is extremely challenging. To help overcome this challenge, it is inevitable that lecturers facilitating the lab activities might need to provide students with some guidance, especially when it comes to more open-ended problem solving. However, as lecturers, we have to be mindful that providing guidance does not mean providing students with solutions to the problems; rather it is about encouraging their thinking and activating prior knowledge that they could possibly make connections with. The quality of their solutions generally showed improvement, and students also agreed that the guidance provided did help them better comprehend the problem and coupled with the guidance provided by lecturers, they could solve the given problems with greater ease.

The second challenge is how to provide students with real plant operations experience at laboratory level. We agreed with the students' viewpoint that curriculum integration is best achieved through actual plant experience. On the other hand, we also acknowledged that whether students are able to gain the relevant plant experience during industrial training programs to allow curriculum integration largely depends on the company they have been posted to and the job scope assigned to them. Luckier students who were posted to the oil and gas or petrochemical plants might stand a higher chance to perform job functions which allow them to practice what they had learnt in the chemical engineering curriculum, while a significant number of students might be assigned to more administrative roles which have limited room for them to put into practice knowledge and skills learnt in campus.

The third challenge identified is how to avoid students from working in silos when working on the practical activities. Students commonly agreed that one obstacle for curriculum integration using activities is that they have the tendency to apply "teamwork" by distributing the work to complete the tasks and assignments among the team mates. As a result, students have the tendency just to focus on the areas which they have been assigned to, complete their portion of their assignment and submit it to a team mate who does the overall compilation of the report. The completion of their respective portions were usually done with little consideration on how the different sections of the report could be interlinked and how solutions to an earlier problem could be applied to solve subsequent ones. Students generally agreed that it is being optimistic to say that one student from a group who puts in effort to compile the lab assignment at the very end would read and comprehend the submissions of their team mates, and edit the submission to make the entire submission cohesive and fluent. This is because on most occasions, students who compile individual contributions have the tendency to just "cut and paste" all different sections together for submission.

From the Reflective Journals submitted by the students, we obtained varied responses. On one hand, there are some students who reported focusing too much on the process instrumentation and control concepts and faced difficulties trying to interlink and integrate the different concepts across the curriculum into the task while, on the other hand, there are others who do not face such challenges. Using a Reflective Journal is a relatively new experience for us, and we need to improve its usage to be able to capture key aspects of the learning process and subsequently make better inferences and interpretations from the response data.

Overall, the results obtained were encouraging. Student feedback supported ‘hands-on’ work opportunities in helping them to apply knowledge and skills learnt in an operational level beyond just a paper exercise, and that is what the *PDP* cannot achieve. Students feedback highlighted the importance of good activity structuring in which the learning experience was made more interesting and meaningful; i.e. before the commencement of practical work, students were required to answer a set of pre-experimental assessment questions, which were crafted in such a way that they are task specific questions (rather than questions for which the answers can be directly retrieved from lecture notes) to help them understand the scenario better and why the task was performed in a particular manner or sequence. Questions were also posed to them during the experiment which served as learning “check-points” to verify students’ understanding of the activity and its related concepts during the course of performing the experiment itself. Lastly, post-experiment and report assessment questions were introduced to help students consolidate the critical learning points; and, more importantly, how *PI&C* concepts learnt in the activity can be integrated and linked to different subject areas within and beyond chemical engineering. In conclusion, the re-designed activities allowed students to apply and practice C-D-I-O skills to design and formulate their solution to the problem, implement and optimize it and, as a result, better retain the knowledge and skills learnt. This is supported by better performance during the semestral examination.

REFLECTION OF CDIO PEDAGOGICAL EXPERIENCE (FIRST AUTHOR) AND RECOMMENDATIONS FOR FUTURE WORK

The CDIO pedagogy was something new to me until I joined SP as a DCHE Lecturer. I belong to the typical group of chemical engineering students who completed my laboratory activities, plant design and final year projects without much excitement that I had learnt new knowledge and skills that will benefit me as a future chemical engineer. It was only after I began employment in the chemical industry that I started to find meaning in what I had studied. I touched and operated live size rotating equipment, furnace, distillation columns, heat exchangers, and DCS for the first time in my life, and I finally understood the process, health and safety considerations behind the design and operation of each plant equipment and process which I could relate to my academic experience.

I was fortunate to be given the opportunity to design and conduct competency based training programs for prospective and in-employment chemical engineers and process technicians as I build up my working experience. Because I do not wish to see my students following my learning footsteps as a typical chemical engineering student, I believed that learners must be able to understand the reason behind every action they perform, and learning is best achieved through active experimentation, and allowing room to make mistakes. Based on my work experiences, I was familiar with the concept of active learning, but not CDIO. It was after my first rigorous exposure to CDIO through the redesigning and implementation of the activities for *PI&C* that I began to realize that CDIO is more than another curriculum framework. It provides a holistic approach to design a meaningful learning experience for students; that requires them to draw upon their prior knowledge of various knowledge bases, applying them to formulate a solution to a task, implementing the solution they had formulated, reviewing the effectiveness of their implemented solutions and making improvisations to refine their solution. In short, I am able to design an integrated learning experience “the CDIO way” that allows students to learn in a more holistic and real world manner.

Several areas have been identified for improvement to achieve further curriculum integration. One possible area is the use of concept maps [12] to assess the achievement of the intended outcomes in an integrated curriculum. In the past twenty years, concepts map have been used to teach and assess conceptual understanding in mathematics and science education. Now these tools are being applied to humanities and social sciences, and to some extent in engineering education. We recognize that this practice had not been employed in our curriculum; and both faculty and students need to be adequately trained on how to draw concept maps in order for it to be a fair and valid assessment.

The remaining practicals in *PI&C* also offer opportunities to further strengthen the integration effort. We intend to purchase integrated pilot plants with the control of multiple equipment (e.g., tanks, pumps, reactors, etc), process parameters (flow, level, temperature, etc), redundancies and safety instrumented systems. I envision the improved *PI&C* practical sessions to firstly allow students to better apply systems thinking techniques in the plant operation and control because they will be able to better visualize how deviation in one process parameter can affect other downstream process parameters. For example, when a storage tank containing feed to a distillation column reaches a low level, it will cause the feed pump to trip. Students need to analyze how this loss of feed to the column is going to impact the liquid level, temperature and hence product distribution in the column. They will then need to take prompt actions to prevent the problem from worsening and restore the process to its safe condition; knowing that failure to do so will result in activation of the safety instrumented systems.

Encouraged by the positive outcome obtained so far, I look forward to revamp the remaining activities within the module along with the introduction of new integrated process units. However, I am also mindful that at the same time, while I intend to further implement curriculum integration to supplement capstone projects, the learning of *PI&C* should still be the primary focus, in view that knowledge and skills in the module will still likely remain an important aspect of chemical engineering. It is through accurate and timely process instrumentation and control that provides a process with maximum throughput, minimum downtime and waste generation and these humbly contributes towards sustainable development.

CONCLUSION

We had successfully completed a trial run of our integration curriculum using *PI&C*. Preliminary results from students' learning experience indicate that they enjoyed the sessions and found studying the subject more interesting and meaningful. With this, we hope to achieve "teaching for transfer and thoughtful learning" that Perkins [13] had advocated:

> "A concern with connecting things up, with integrating ideas, within and across subject matters, and with elements of out-of-school life, inherently is a concern with understanding in a broader and a deeper sense. Accordingly there is a natural alliance between those making a special effort to teach for understanding and those making a special effort toward integrative education."

We will make use of the learning points identified above to continue to revise the remaining activities and improve on the module using CDIO.

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