Enhancing the CDIO learning experience through industrial partnered real world engineering projects

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ABSTRACT

This paper documents how final year students at Singapore Polytechnic (SP), involved in the Conceive-Design-Implement-Operate (CDIO) curriculum initiative, participated in a real world engineering project that resulted in the successful development of a small scale ecological human waste disposal sanitation system. The strategic importance and role of the industrial partner is highlighted as well as the pedagogical approaches that underpinned the various key stages of the student experience.

The paper firstly outlines the broad approach that has been taken by SP in customizing the general CDIO syllabus to the polytechnic context and, in particular, addressing the two central questions posed by Crawley et al (2007):

- What is the full set of knowledge, skills and attitudes that engineering students should possess as they leave the university, and at what level of proficiency?
- How can we do better at ensuring that students learn these skills?

We will attempt to show how the use of such projects enables the integration of skills across the four high level categories of CDIO learning outcomes:

1. Technical knowledge and reasoning
2. Personal and professional skills and attributes
3. Interpersonal skills, teamwork and communications
4. Conceiving, Designing, Implementing, and Operating systems in the enterprise and societal context

Secondly, we document how an active and experiential learning approach, underpinned by sound pedagogical principles, led to more meaningful and deep learning, as experienced by the students. It will be noted that the management of learning in such projects needs a wider pedagogic frame than simply ensuring activity and experience per se.

The different stages of the CDIO process are described and related to the various stages of the project. We highlight the importance of effective communication and relationship building with industrial partners and the often messy process of aligning perceptions about how best to conduct different project activities and engineering design. Students were exposed to the reality of engineering work in the real world context in which interpersonal and other negotiation skills can become as important as technical competence in getting work done. It is often the case that many alterations are needed in design as a result of different framing of the situation and outcome perceptions.

We started the project based on how to conceive, design and build a 2 stage digestor to handle toilet waste coming from portable toilets at a camp site, and this led to even more changes during the implementation stage when constraints of resources led to a complete re-design of the 2 stage digestor. It was only during the operate stage, that we were able to highlight some of the successful test results using the product of the system (in this case actual manure) as a proof that the design actually worked in practice. The project was successful in the final stage of the CDIO process, where the 2 stage digestor was verified for its efficacy through direct potting with alfafa plants and comparisons made directly with other manures.

Finally, the paper summarizes how the learning experiences that the students went through can provide authentic real world engineering insights well beyond the confines of the more theoretical learning of engineering science in the classroom context. Furthermore, students were able to relate how engineering products significantly impact the societal context, in this case potentially enhancing aspects of the quality of life in a number of third world countries.

KEYWORDS

Real world engineering, industrial partner, active and experiential learning, skills integration, student learning experiences

INTRODUCTION

The department of Chemical Engineering at Singapore Polytechnic (SP) implemented the CDIO framework in 2007, which has subsequently resulted in a major curriculum reframing to meet selected CDIO Standards (e.g., syllabus outcomes, integrated curriculum, integrated learning experiences and active learning). As a result the curriculum learning outcomes, teaching/learning strategies and assessment practices have become orientated towards a more real world engineering focus.
A major part of the curriculum revamp, apart from the critical review of the technical knowledge and skills of the programmes, was the systematic infusion of a range of CDIO skills into our course and module structures. A particular focus was on critical and creative thinking, systems thinking and managing learning (personal & professional skills and attributes), teamwork and communication (interpersonal skills) and conceiving, designing, implementing, and operating systems in a real world engineering context.

In this paper, we firstly outline the broad approach that has been taken by SP in customizing the general CDIO syllabus to the polytechnic context and, in particular, addressing the two central questions for reframing engineering education as posed by Crawley et al (2007)[1]:

- *What is the full set of knowledge, skills, and attitudes that engineering students should possess as they leave the university, and at what level of proficiency?*
- *How can we do better at ensuring that students learn these skills?(p.34)*

Secondly, we document an industrial partnered project in which final year student students were involved in conceiving, designing, implementing and operating a small scale ecological human waste disposal sanitation system. This constituted an adventurous active and experiential learning experience in which students had the opportunity to integrate both disciplinary knowledge, personal and interpersonal skills and product, process and system building skills.

Finally, we summarize the key learning points from the project experience, highlighting the potential benefits in terms of student learning, as well as the challenges for faculty in creating such learning experiences.

CUSTOMIZING CDIO TO THE POLYTECHNIC CONTEXT

The original CDIO Skills framework was the product of a comprehensive stakeholder focus group exercise comprised of engineering faculty, students, industry representatives, university review committees, alumni, and senior academicians. The resulting CDIO Syllabus classifies learning outcomes into four high-level categories:

1. Technical knowledge and reasoning
2. Personal and professional skills and attributes
3. Interpersonal skills: teamwork and communication
4. Conceiving, designing, implementing, and operating systems in the enterprise and societal context.

These high level categories are further subdivided and organized into four discrete rational levels. While levels 1 & 2 are generic and specified, the selection of level 3 & 4 learning outcomes and the level of proficiency is within the framing of individual educational institutions, customized to the course context and stakeholder needs. The recommended process for establishing proficiency levels and learning outcomes is as follows:

- Review the generic CDIO Syllabus and make modifications or additions to customize it for a specific course of study within the technical and national context of the program.
- Identify and survey the important stakeholders of the program – both internal and external to the university – and validate their coverage and proficiency level to the local context
- Write specific learning outcomes that guide the design of learning and define the assessment requirements

This we felt was a critical process for the success of the curriculum innovation. Limitations in the appropriateness, clarity and currency of the learning objectives inevitably run through the instructional and assessment systems. There's limited value in teaching and assessing a knowledge or skill area in effective and efficient ways if it has little or no relevance to stakeholder interests.

Furthermore, as Diamond (1998) [2] points out:

> *…it is a major mistake to take any published list of basic skills or competencies and accept it for use on another campus without revision. Not only will the specific items on such a list vary from institution to institution but the definition of each item will vary as well. The final list of competencies, their definitions, and how they should be assessed must evolve on each campus. Faculty ownership in the process is an essential element for success. (p.53)*

In order to ensure that the CDIO skills at levels 3 & 4 were most appropriate to the context of students at Singapore Polytechnic a working group of representatives from the various engineering schools was established to systematically work through all the CDIO Skills, with a remit to:

- Identify which skills were most appropriate in the SP context
- Decide a viable proficiency level
- Write specific learning objectives that are measurable at level 4

The result of this process has been the creation of a fully customized CDIO syllabus to the proficiency level of polytechnic students in the Singapore context.

In terms of the CDIO pedagogic approach, this has been broadly documented elsewhere. For example Crawley (2007) et al stated:

> *…we recommend improvement in two basic areas: 1) an increase in active and experiential learning, and 2) the creation of integrated learning experiences that lead to the acquisition of both disciplinary knowledge, personal and interpersonal skills; and product, process and system building skills (p.29)*

Active and experiential learning are not new pedagogic approaches. They have been extensively and successfully employed in a wide range of teaching and training contexts for many years. Essentially, active learning happens when students are given the opportunity to take a more interactive relationship with the subject matter of a course, encouraging them to generate rather than simply to receive knowledge. As Chickering and Gamson (1987) [3] pointed out:

> *Learning is not a spectator sport. Students do not learn much just by sitting in class listening to teachers, memorizing pre-packaged assignments, and spitting out answers. They must talk about what they are learning, write about it, relate it to past experiences, apply it to their daily lives. They must make what they learn part of themselves (p.3)*

Active learning methods, when used effectively, engage students directly in the learning process, making possible the use of good thinking in relation to the key concepts, principles and procedures of subject disciplines. These are the very cognitive processes that enable learners to make meaning of their learning and build understanding, which makes possible the transfer of learning. The transfer of learning is as McTighe &Wiggins (1998) [4] point out:

> *…our great and difficult mission because we need to put students in a position to learn far more, on their own, than they can ever learn from us. (p.44)*

It is important therefore, to have a well constituted pedagogical approach that facilitates the integration of knowledge, skills and processes in the context of an active real world learning experience. This was exactly the kind of experience that was intended in the industry partnered project.

THE PROJECT: CONTEXT & PROCESS

Human waste disposal is a significant problem, especially in third world economies with increasing populations. Treatment processes can broadly be classified into two basic options – aerobic or anaerobic. The aerobic treatment process we have in Singapore, and many developed cities, is energy intensive. Processes include clarification, aeration, sludge thickening, sludge digestion and dewatering are often carried out, ensuring the sludge is safe, before it is being disposed at reclaimed land as soil conditioner. But with the increasing cost of fuel and energy, it has become increasingly difficult to justify the use of energy to treat something as lowly as human waste. The anaerobic option, which does not require energy input for breaking down its constituents, has increasingly found favor due to its low energy treatment footprint and a concomitant production of useful energy for reuse.

Our investigations here are in line with global research [5], [6], [7] trends to minimize energy use and reduce green house gas emission. In this project we investigated the viability of anaerobic treatment through the use of a modified dual-digestion system. In essence, we had mesophilic anaerobic digestion occurring before thermophilic aerobic digestion to decompose the human waste. Our design and construction resulted in some energy recovery and at the same time was capable of producing safe and useful manure for planting.

The real world engineering aspect of the project was largely conducted by the students, aided by our industrial partner, while the stages of CDIO were taught to them through reinforcement by the project supervisor at each stage of the process.

The following comment from a student participant reflects the ability of the project to engage learning outcomes 1 and 3 of the four high-level categories in the CDIO framework quite successfully:

> *We learnt that we have to design a waste recovery digester and place it on the farm itself. Also, we have to work with the owner and the person-in-charge who is handling SVF. We also realize that to complete a project successfully, we have to held responsibility of working with people. It is important to incorporate the skills of communicating with others. This interpersonal communication skill is important as it determines whether the other party is willing to help us. We also have to incorporate these skills to plan and organize meetings session with people involving the construction of digester. (Tang Poh Ling)*

At each stage of the project, students met regularly with the industrial partner to find out the constraints and availability of resources. After each intervention, they revised their design until the final design fitted technical, costs and environmental considerations.

The following comment reflects the presence of active and experiential learning over and above the disciplinary knowledge taught in the classroom.

> *We have learnt some interesting design ideas from Dr. Han which are cheap and innovative. We also learnt that expensive equipment may not be needed for accurate measurement. With a little innovative idea, money could be saved. (Gerry Neo)*

Here, increased participation of an industrial partner brought about the transfer of simple industrial knowhow not normally taught in the classroom. Both the students and the industry stand to benefit from this collaborative relationship. In the following section, we provide a summary frame on the key learning experiences of the students and project development outcomes at different stages of the CDIO process.

CDIO - Conceive Stage

During this stage of the project, students were very much involved in discussions with their project supervisors and the industrial partner, Singapore Vision Farm (SVF), generating essential questions and ideas for subsequent analysis and evaluation. The requirements of the project were listed as follows:

1. System to fit SVF site requirements
2. Technical reference to ATAD design
3. Solve the waste discharge from portable toilets on SVF, and relate the solution to the overarching societal concerns of waste disposal in third world economies.
4. Test bed the manure produce with potted plants, and relate to farming needs in agrarian societies.

Based on these requirements, the project team set out to design a digester system consisting of 3 main process stages. The design that emerged from the discussion consisted of a (1) settling zone, (2) Mesophilic anaerobic treatment and (3) Thermophilic aerobic treatment. The sludge digestion process is illustrated on Figure 1.

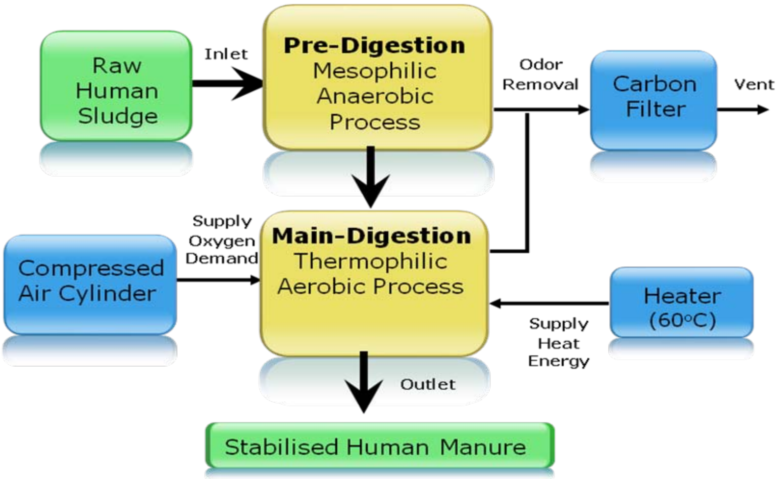

Figure 1: Flow Diagram of Sludge Digestion Process

Next, the team crafted a design to ensure the digestor fitted the requirements of SVF. The considerations included a ground pit, a novel design of a sieve plate to concentrate the solids from the portable toilet discharge. Finally, the team planned various tests they would conduct with the digestor output from the 2 stages.

Throughout the entire Conceive process the students had many discussions with both the supervisor and the industrial partner. The need for clear, concise and accurate communication left a powerful mark on them as can be seen in the following reflection by one student:

> *We learnt that communication and information given to other people is very important. It must be very clear so people will not misinterpret the actual meaning that the speaker is trying to express. (Tai Zhang Hao)*

The first overall design, as worked out with our industrial partner is shown in Figure 2. The drawings were sketched out by our industrial partner using Microsoft Excel. This serves as a framework for discussion, as equipment and process sizing were not done in detail. The drawings serve as a guide to every project member of how things should work out. This is illustrated in Figure 2.

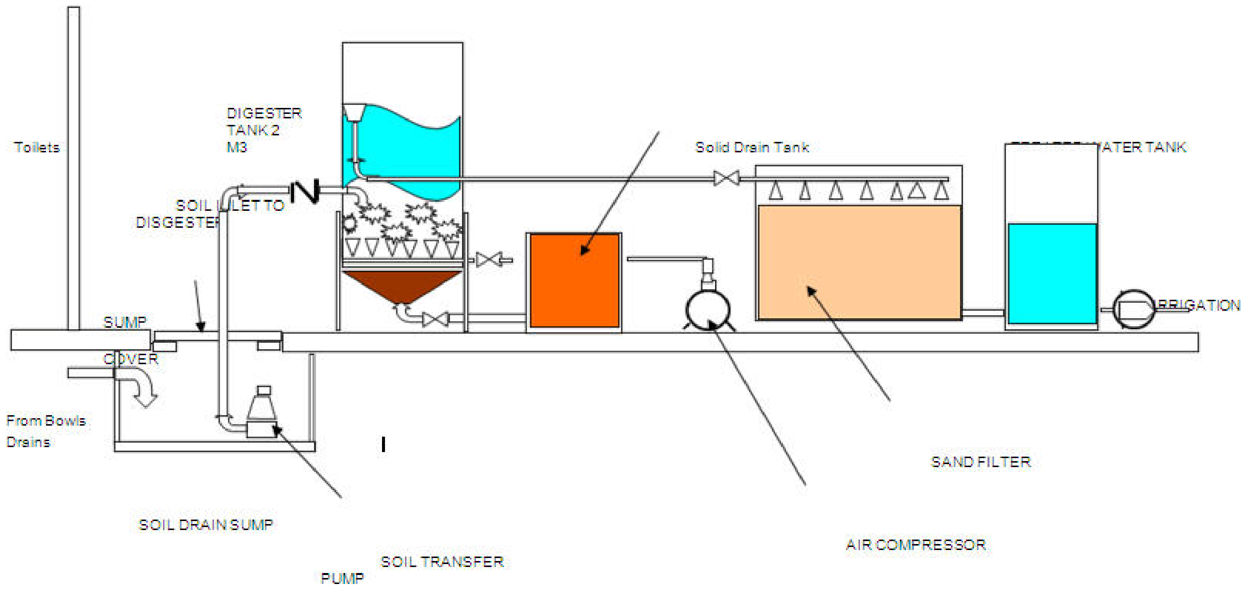

Figure 2: Overall View of Initial Design

CDIO - Design Stage

After finalising the first stage of the CDIO process, the team proceeded to brainstorm for ideas on the technical design of the system. Students quickly realized they do not have all the design information they need to come up with a prototype. To compound the problem, there was no ready-made model answer or solution. This was so unlike their classroom encounters. Recollections of the process encountered, as in the example below, revealed a sense of achievement in coming up with something they never thought possible:

> *During brainstorming of prototype design, we use simple but innovative way to develop the design. In this way, we have developed a new method of testing presence of gas in the surrounding. (Tang Poh Ling)*

At this point, the team had to reframe their understanding of the overall ATAD design with the 2PAD Disgestion System [8], and verified that the 2 stage digestor could operate in the manner they brainstormed. Subsequently, the team produced their first design drawings, as shown in Figure 3.

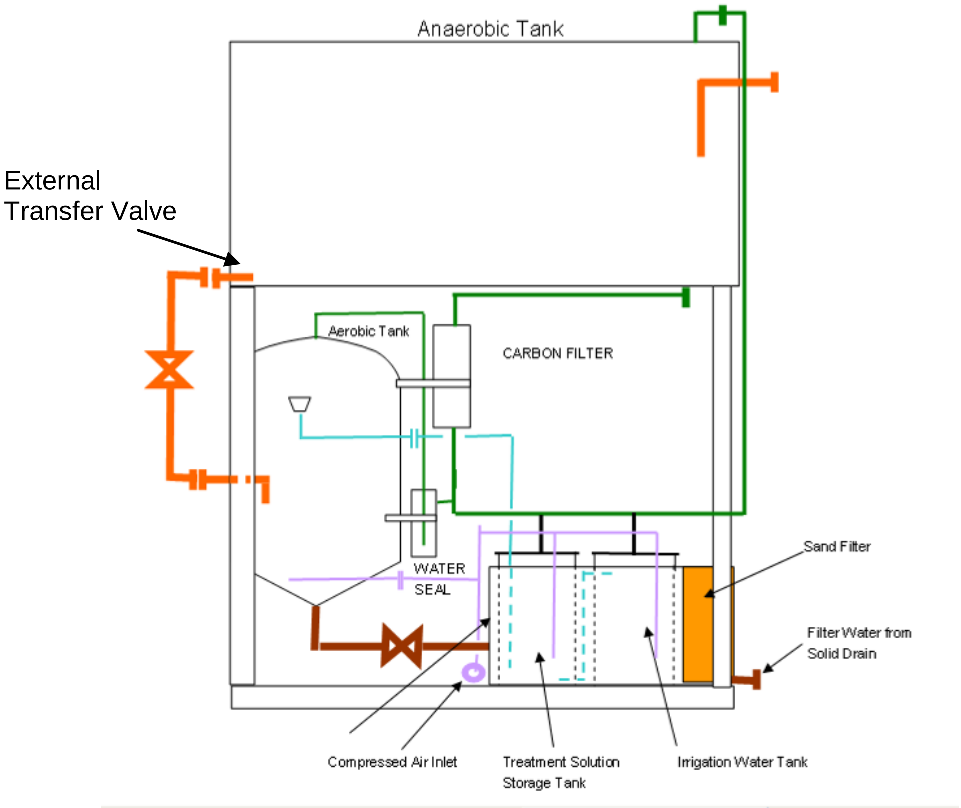

Figure 3. Engineering Design

The anaerobic and aerobic stages are housed in 2 separate vessels. The inter-vessel transfer is handled by an external valve (on the left). Other parts in the system, not shown in drawing, include the provision of an underground pit, water seal, sludge pump, filtering system, waste storage tank and an irrigation pump.

CDIO - Implement Stage

After much prototyping, experimentation, as well as consideration of the various constraints identified by our industrial sponsor, the team simplified the design of Figure 3 into the final form shown in Figure 4 below. The site constraints encountered included the availability of materials, the solid/liquid ratio of sludge and location limitation of Inspection Chamber within the site.

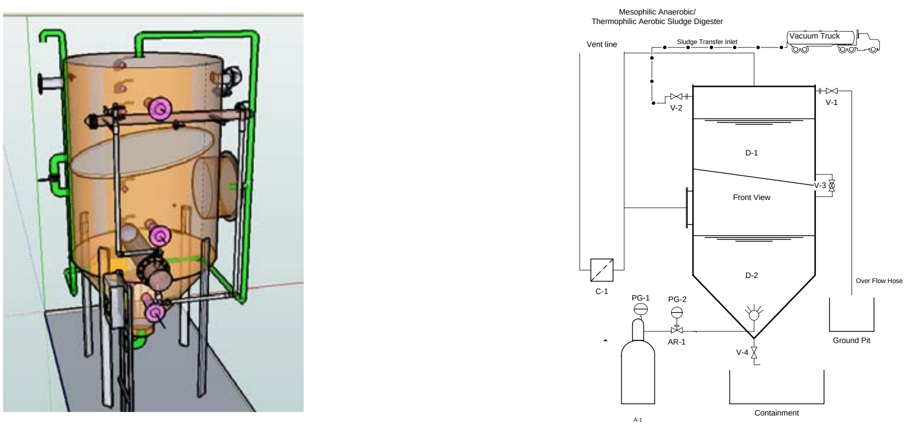

Figure 4: Final Design

During the implement stage of the CDIO process, the students transformed their design to fit the constrains of industrial partner (SVF). The reason behind the transformation in design from Figure 3 to Figure 4 was cost. To cut cost, our industrial partner suggested the use of an existing single conical vessel left over from his work on another project. As a result of this new information, the students have to re-design their 2 vessel system into a single vessel design. In real engineering terms, they had faced a real world time-resource constraint as they need to quickly re-engineer their design to the new situation. Fortunately, they rose to the occasion and quickly collapsed the initial design of 2 separate digestor tanks into 1, which is shown in Figure 4. In tweaking the design, they also replaced the design for a inter-vessel valve with a sloping plate discharge for inter-vessel transfer. The replacement came about also partly because of the difficulty in practical terms of installing a valve in between the two vessels (now collapsed into 1) and yet maintaining a air tight seal.

Students appreciated the learning experience in the CDIO implement process as they come to see for the first time what textbook teaching can never achieve. Below is a representative example of how the setting of an experiential and integrated learning environmet enhanced students ablity to think and subsequently reframe their solutions to problems encountered:

> *We have learnt that not every construction plan can go according to what u have plan. One has to be quick to adapt to changes so that things could go on smoothly. This allows us to learn to adapt to changes fast and improve. (Gerry Neo)*

The final design is shown in Figure 5 below.

Fully Equipped Digester System

Figure 5: Final Digester

CDIO - Operate Stage with Alfalfa Plant

In this last stage of the CDIO process, the link between a good engineering design and its value in the real world is established. Students at this stage look forward eagerly to verify their design. This stage also provided a perspective in which they could relate their work to societal concerns in waste disposal in third world economies, and its significance to helping agrarian societies. This helps to encourage a global mindset among our students, which is very difficult in a traditional classroom context. Students at this stage were able to use their disciplinary knowledge in experimental design to customize an experiment to test the efficacy of their digestor output – human manure.

The selection of plant species was critical. They selected Alfalfa plants on their own initiative without guidance and correctly identified the plant's sensitivity to nutrient deficiencies and it's availability on campus amongst other project groups. This seems evidence of good transfer of learning resulting from working on real world problems in the CDIO context.

The project team planted a total of four pots of Alfalfa seeds. Pot 1 (Blank) is not treated with any nutrients and acts as a control to compare with the nutrient uptake ability of Pot 2 using human manure. Pot 3 (Potting Soil) uses commercialized packet organic plot soil. Lastly, Pot 4 (Bird Manure) is seeded with bird manure. Figure 6 below shows the four pots placed next to each other to ensure a consistent environment (e.g., amount of sunlight and heat).

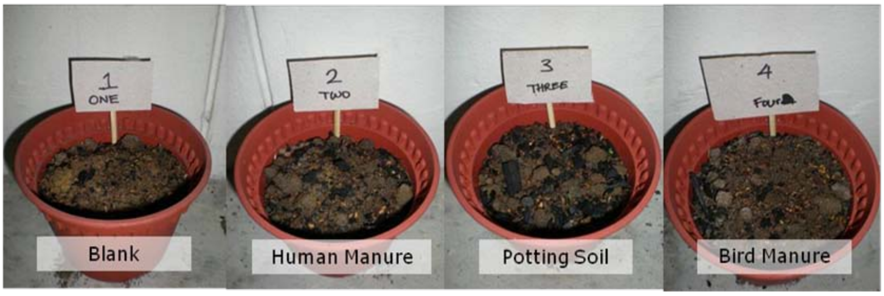

Figure 6: Initial Stage of Experiment

The active and experiential learning process was continued as students had to wait 11 weeks to see growth in the young alfalfa plants. They were able to compare and contrast Pot 2 (Human Manure) to Pot 1 (Blank) and effectively deduce the noticeable growth indicating uptake of human manure nutrient by the plant (Figure 7). There were more and greener leaves which were also taller as compared to the blank Pot 1. Thus, they were able to conclude that the human manure they produced was capable of good plant growth. They were also able to make comparisons with other organic fertilizers. For example, in Pot 3 (potting soil) and Pot 4 (bird manure) the results were shorter plant and lower leaf counts. Overall, their results showed that human manure can be utilized widely as part of our crops fertilizer application. This provided evidence to our students on the suitability of their 2 stage design in real world practice.

Figure 7: Developed Young Alfalfa plants

ENHANCED LEARNING EXPERIENCES

From our observations and student feedback it was apparent that the infusion of the CDIO process, by providing the essential structure to model real world of engineering practice, resulted in more meaningful and deeper student learning, as well as success in project outcomes. Some of the salient learning benefits included:

1. It allows the student to achieve new outcomes not originally thought possible.
   - working with an external party provided them with real world working experience that classroom teaching cannot achieve
   - learning responsible behavior through making appointments and sticking to schedule
   - adaptability and flexibility in design when faced with constrains on the ground

2. Collaboration with the industry
   - gave our students “interesting design ideas” that textbooks can never provide simply because they were never documented in writing

- brought realism into the engineering design as students grapple with the ever changing demands impose on them by the industrial partner

3. Prepares our students for the knowledge economy [9]
   - importance of communication skills to avoid unnecessary delays in project schedule
   - develop good personal and interpersonal skills

In terms of the project outcomes, the promising results support the potential suitability of the 2 stage design for producing human manure, which may be used in third world economies to supplement costly chemical fertilizers. However, we acknowledge that more research is required in order to verify the effects of pharmaceuticals and endocrine disruption compounds.

SUMMARY & FUTURE ACTION

The project started as a test case of CDIO principles in real world engineering problem-solving context. Through industry sponsored partnership an added authenticity was provided to give the students more than a simulated experiential learning experience, but an actual real world one. This enabled us to provide a context of learning that was difficult to achieve in the more formal institutional setting. In our case, we provided active and experiential learning opportunities to students through project work involving active support from an industry partner in solving a real world engineering problem. We observed from our initial results, that this integrated learning experience can, in fact, lead to the acquisition of both disciplinary knowledge, personal and interpersonal skills in the students who participated in the project.

From the various feedback and comments from the students, we are encouraged to further develop the use of this mode of integrated learning experience through active and experiential participation in real world engineering projects. Furthermore, as the opportunity for creating these powerful learning experiences for our students is dependent on the strong support of the industry, much works needs to be done in building collaborative relationships with industry partners. In moving forward, we see the necessity developing more collaborative relationships with appropriate industrial partners who see mutual benefits in working collaboratively with us.

For a final reflective frame, we offer a comment from a student (now working with Exxon Chemicals Singapore) on the impact of the CDIO experience on her working practices:

> *I think I'm consistently applying it unconsciously in my working life as I tend to get the same benefit from CDIO but not remembering that I follow any CDIO rule. (Tang Poh Ling)*

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Biographical Information

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Dennis Sale is presently Senior Education Advisor at Singapore Polytechnic. He has worked across all sectors of the British educational system and provided a wide range of consultancies in both public and private sector organizations in the UK and several Asian countries. His specialist areas include *Creative Teaching* and *Curriculum Development*. He has invented highly effective and practical models in these areas, conducted numerous workshops in all educational contexts and many countries, presented papers at international conferences and published in a variety of journals and books.

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