CHEMICAL PRODUCT DESIGN AS FOUNDATION FOR EDUCATION AS SUSTAINABLE DEVELOPMENT

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ABSTRACT

This paper shares the experience of the Diploma in Chemical Engineering (DCHE) of Singapore Polytechnic (SP) in using chemical product design which was integrated into all 3 years of its curriculum, to achieve the CDIO goal of “Conceive – Design — Implement — Operate complex value-added engineering systems in a modern team-based engineering environment to create systems and products”. In particular it focuses on the Year 2 module *Chemical Product Design and Development* which serves an important role as a “bridge” that connects together the initial product conceptualization in year 1 until its eventual realization in year 3 *Final Year Projects* (FYPs), i.e. capstone project.

The paper first briefly introduces the DCHE model of Education for Sustainable Development that is built on chemical product design. It explains the emergence of chemical product design in chemical engineering education and the increasing importance of including sustainability principles in product design and development. It explains how a key concept of in product lifecycle analysis (cradle-to-cradle design); and a key competency (systems thinking) are integrated into the module *Chemical Product Design and Development.* The integration of product and process design is also covered in the module.

The paper then describes 3 case studies of sustainable development themed projects to illustrate various works related to sustainable development in realizing the CDIO learning outcomes: (1) Floatable toilet system in Cambodia, (2) Rainwater harvesting system in Nepal, and (3) Herbal soap production in India. Following this, the paper shares 3 key challenges faced in our teaching of this module: (1) Prototyping chemical products, (2) Encouraging students to extend their work done into capstone projects; and (3) Integrating process and product designs as one holistic project for our students. Lastly, it outlines broad areas where we can continue to improve the teaching of this module.

KEYWORDS

Sustainability, chemical engineering, chemical product design, CDIO Standards 3, 5 and 7, systems thinking, social responsibility

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”.

INTRODUCTION

The Diploma in Chemical Engineering (DCHE) in Singapore Polytechnic (SP) developed a model of sustainable education based on the CDIO Framework to transform its chemical engineering education. The resulting curriculum model for Education for Sustainable Development (ESD) meets the dual-purpose of (1) satisfying industry requirements with the necessary technical knowledge and soft skills (CDIO skills), so that the students are competent in the workplace; and (2) encouraging them to serve the broader needs of society, especially those at the bottom-of-the-pyramid. The bottom-of-the-pyramid refers to socio-economic groups consisting the world's poorest citizens constituting an invisible and unserved market blocked by challenging barriers that prevent them from realising their human potential for their own benefit and that of society's at large. Suffice to note here that the model is based on the integration of chemical product design and engineering into the diploma's 3–year curriculum; namely *Introduction to Chemical Product Design* (Year 1), *Chemical Product Design and Development* (Year 2) and *Final Year Project* (Year 3). The DCHE Capstone Project represents the attainment of the CDIO goal of "Conceive – Design — Implement — Operate complex value-added engineering systems in a modern team-based engineering environment to create systems and products", which is illustrated in Figure 1. The other modules in the Chemical Engineering curriculum support the learning of innovative chemical products or systems.

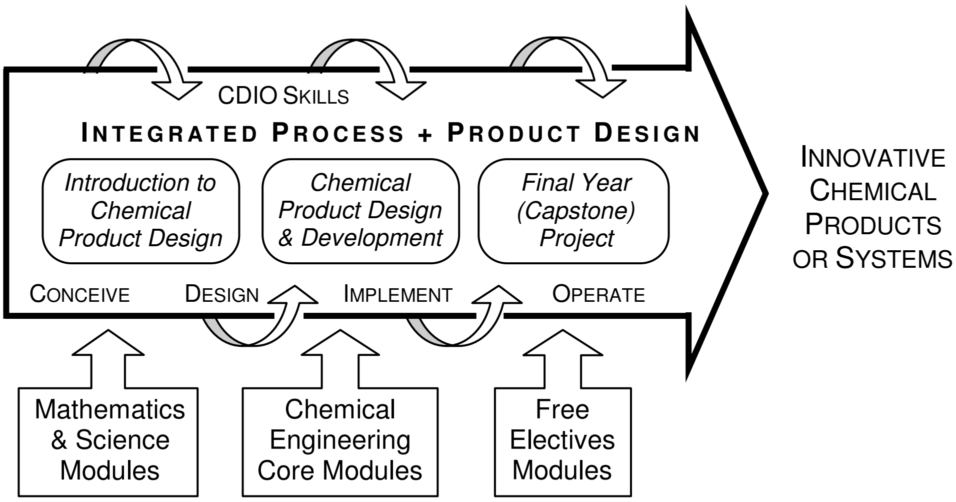

Figure 1. Chemical Engineering Curriculum Model for Sustainability Education

This paper shares our experience in the teaching of the Year-2 module *Chemical Product Design and Development*, which serves the important role as a "bridge" that connects together the initial product conceptualization in year 1 until its eventual realization in year 3. It is in this module that students get to apply the chemical engineering principles learnt in various core modules into chemical product design, as explained in the next sections.

CHEMICAL PRODUCT DESIGN & ENGINEERING

According to Costa and Moggridge (2006), the chemical process industries, which include petroleum, fine chemicals, pharmaceuticals and health, agro and food, have been facing dramatic social, economic and technical challenges, on a global and local scale. As a result, they have been undergoing deep and rapid changes in the scope of their activities and business, in the strategies adopted to remain profitable and achieve sustainable growth and in the way they view the chemical engineering profession. This invariably means that the portfolio of skills and technical knowledge required by chemical engineers has also been changing rapidly.

Henceforth, chemical product design has become more important because of the major changes in the chemical industry. The industry is forced to formulate new strategies to remain competitive. Many chemical companies focus their growth on specialty chemicals or high-performance materials because these are produced in much smaller volumes and commodities. They typically have much higher added value as well. This higher added value means that more research and higher profits are possible and, as a result, many chemical companies are turning their focus to specialty chemicals or high-performance materials.

Integration of Sustainable Development (SD) in Chemical Product Design

Traditionally, product designers have been concerned primarily with product life cycles up to and including the manufacturing step. That focus is changing. Increasingly, chemical product designers must consider how their products will be recycled. They must consider how their customers will use their products and what environmental hazards might arise. Simply stated, chemical engineers must become stewards for their products throughout their life cycles (Narodoslawsky, 2007). These increased responsibilities for products and processes throughout their life cycles have been recognized by a number of professional organisations, such as the American Chemistry Council. Effective product stewardship requires designs that optimize performance throughout the entire life cycle. The aim is to provide an introduction to tools available for assessing the environmental performance of products throughout their life cycles.

In the Year 2 module, *Chemical Product Design and Development*, our students apply a product life cycle that consists of the following stages as shown in Figure 2:

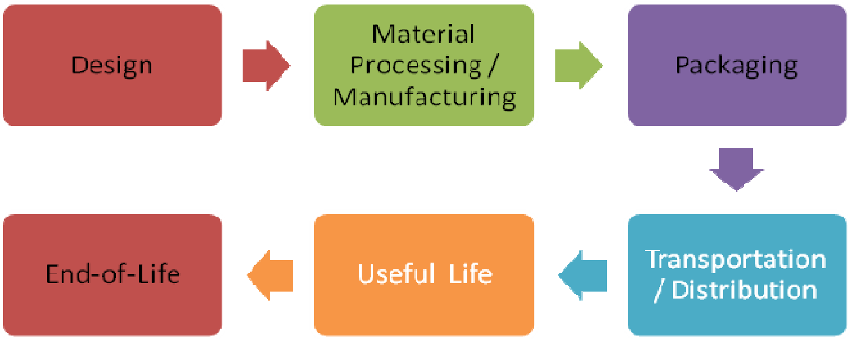

Figure 2. A Generic Product Life Cycle Used in the Module

Our students are encouraged to use various methods of illustration to depict the product life cycle of their product ideas. This is to cultivate their sense of creativity and exhibit their non-engineering hidden talent.

In addition, our students are exposed to the concept of cradle-to-cradle modelled based on nature. According to McDonough and Braungart (2002), the cradle-to-cradle design principles aim to eliminate the concept of waste. It is not reduce, minimise of avoid waste, but to eliminate the very concept by ‘Design’. Students learnt that products and materials shall be designed with life cycles that are safe for human health and environment, and that can be reused perpetually through biological and technical metabolisms. Students also learnt to create and participate in systems to collect and recover the value of these materials following their use.

McDonough and Braungart (2002) advocate 5 ways to achieve cradle-to-cradle design principles. They are:

1. Maximise use of renewable energy
2. Select safe and healthy material
3. Protect water resources
4. Social responsibility
5. Celebrate diversity

Our students are able to appreciate the concept when they compare and contrast the concepts of cradle-to-cradle and cradle-to-grave. Most often, our students cite that their product idea is “recyclable” and hence the concept of cradle-to-cradle is being applied. However, they lack the foresight to recognise that the composition of the product determines how easy the product can be ‘taken apart’ for recycling processes or how biodegradable it is if it is disposed. This served as an important learning point for everyone in the class and the learning is facilitated by the lecturer.

During the course of designing their product, our students integrate their technical knowledge gained over the course of study. It is emphasised that a product’s design can influence each stage of its life cycle and in turn the environment. Students learn the life cycle approach to SD by:

- Making choices for the longer term; avoid short term decisions that lead to environmental degradation
- Avoiding decisions that fix one environmental problem but cause another unexpected or costly environmental problem
- Avoiding shifting problems from one life cycle stage to another

Most of the time, when students are given a problem, they typically identify solution(s) quickly. As a result, the desired outcome is not sufficiently met and often the proposed solutions may make things even worse in the longer term. This is because the impacts or effects of the solutions on other aspects of the wider system configurations may be neglected. Understanding the problems posed by sustainable development requires an understanding of the way in which complex systems behave and can be managed (Clift, 2004). Thus, our students are also taught to apply Systems Thinking in chemical product design. By using Systems Thinking, we hope that they can see the connections within the system and with other interacting systems. In another words, by altering the properties, capabilities or behaviours of any parts or any interactions, it affects other parts, the whole system and interacting systems.

When applying Systems Thinking in chemical product design, our students are required to investigate the following:

1. Identify individual components of the chemical product.
2. How do the components affect each other?
3. How do the parts together produce an effect that is different from each part on its own?
4. How does the effect persist in a variety of circumstances?

In addition, our students also apply Systems Thinking to consider how aspects of the external environment interact with the chemical product. The external environment can include both physical features as well as social, cultural or political surroundings.

The students' knowledge, skills and attitudes acquired through the conduct of various activities are assessed by the respective facilitators. Comprehensive assessment rubrics have been developed for all activities facilitated in the *Chemical Product Design and Development* module. The Level of Outcome is based on a scale of 1 to 5. One such example pertaining to the activities described in this paper is as follows:

Assessment Component	Level of Outcome				
	1	2	3	4	5
Analyse the technical system	Problem goal stated is **very vague**. Options to meet the goal stated are **inappropriate or unsuitable**. **Very poor** use of language.	Problem goal stated is **vague**. Options to meet the goal stated are **limited and lacks clarity and**. **Poor** use of language.	Problem goal is **stated**. Options to meet the goal are **stated but limited**. Use of language is **appropriate**.	Problem goal is stated **clearly**. Options to meet the goal are **stated and concise**. Use of language is **appropriate**.	Problem goal is stated **very clearly**. Options to meet the goal are **clearly stated and concise**. **Good** use of language.
Suggest appropriate engineering concept(s)	Engineering concept(s) is/are **unrealistic**.	Engineering concept(s) is/are **impractical**.	Engineering concept(s) is/are **somewhat sensible**.	Engineering concept(s) is/are **sensible but not pragmatic**.	Engineering concept(s) is/are **logical**, **realistic and pragmatic**.
Description of Product Life Cycle	**Very poorly** written description and use of language. **Many mistakes** in spelling.	Description **lacks clarity and poor** use of language. **Some mistakes** in spelling.	**Fairly well written** description and use of language. **Occasional** mistakes in spelling.	Description is **clear and concise**. Use of language is **appropriate**. **Occasional** mistakes in spelling.	Description is **clear, concise and fully communicates all** relevant information. **Good** use of language. **No** spelling mistakes.
Product Life Cycle diagram	**Very poorly** constructed diagram with many **incomplete** information.	Diagram is **poorly constructed** with some **missing** information.	Diagram is **generally clear and well constructed**, with **some** pictures, and contains **sufficient** information.	Diagram is **generally clear and well constructed**, with use of pictures, and contains **sufficient** information.	Diagram is **well constructed**, with **appropriate use** of pictures, and contains **relevant** information.
Application of cradle-to-cradle concept Application of systems thinking	**Very poor** application of concept and use of language.	**Poor** application of concept and use of language.	Application of concept is **fairly well written**. Use of language is **appropriate**.	Application of concept is **clear and concise**. Use of language is **appropriate**.	Application of concept is **clear**, **concise and fully communicates all** relevant information. **Good** use of language.

Table 1. Assessment Rubrics for Assessing Student Knowledge, Skills and Attitude

In addition, students are required to complete and submit a peer assessment to evaluate each of their team members' contribution towards the work completed. The purpose is to discourage any free riders.

Chemical Product Design vs Chemical Process Design

After designing a product, our students need to realize that a series of processes are required to manufacture the product. Hence, there is a need to integrate chemical product design with process design, as depicted in Figure 3.

In chemical product design, the desired product qualities, needs and a set of targeted properties are defined in relation to customer needs. Based on this information, ideas are generated, which are then tested and evaluated to identify the chemicals and/or mixtures that satisfy the desired product specifications. The next step is to select one of the product ideas and design a process that can manufacture the product. On the other hand, in chemical process design, the specifications of the chemical product and its desired qualities are known. Based on this information, a series of decisions and calculations are made at various stages of the design process to obtain first a conceptual process design, which is then further developed to obtain a final design.

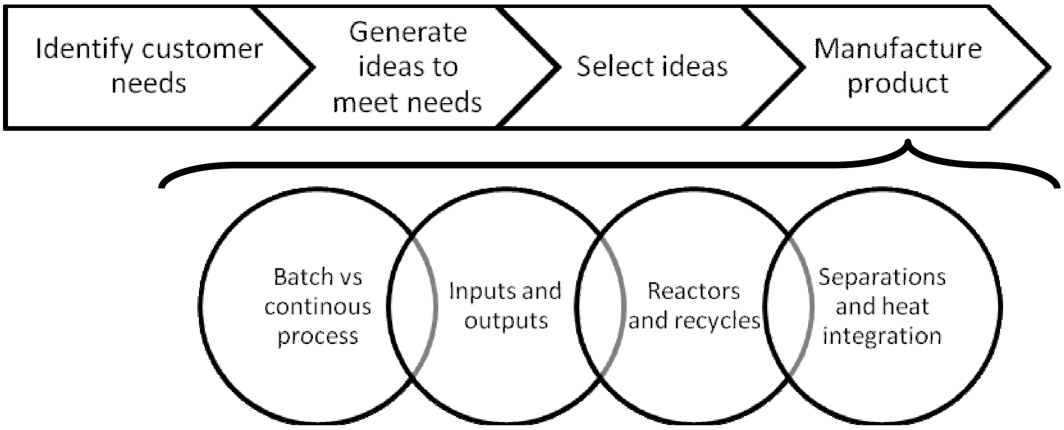

Figure 3. Integration of Product Design with Process Design

According to Cussler and Moggridge (2001), the important step in product design is to anticipate components of the process design, which is the manufacture of the product. First, it is necessary to decide whether a process is batch or continuous. Then, the inputs and outputs are determined on flow sheets and usually chemical reactions are involved. The next step involves the addition of recycles. Once the main processes are established, various separation processes and heat integrations are incorporated.

With our students taking *Chemical Product Design and Development* module in their second year of study, it provides them time and opportunities to refine their ideas and explore the technical feasibility of realizing the product. With the refinement and exploration, they can then implement a workable product or system during the course of their *Final Year Project*. We strongly encouraged our students to submit proposals for student-initiated projects.

SELECTED CASE STUDIES OF SUSTAINABLE DEVELOPMENT-THEMED PROJECTS

The major outcome of our curriculum model is that it enables us to engage our students in coming up with innovative chemical products and/or systems for their capstone projects that meet the needs of sustainability. Our emphasis here is not just on students being able to integrate their technical knowledge gained over the years of study, but also to demonstrate understanding in considering social and economic aspects of sustainable development as well. This outcome is to be attained by learning about product design right from Year 1 that is further refined in Year 2 and eventually realised in Year 3. Anything that is new and useful to a community can be seen in terms of innovation, even if similar products are available elsewhere or if the change is an incremental one.

Students who are involved in these projects served the needs of the bottom-of-the-pyramid society. In addition to applying their technical knowledge, it provides opportunities for them to develop their social responsibilities beyond the local context. At the same time, it also creates social responsibility awareness amongst their peers and let them realise that engineering products and systems can be driven by social, environmental or sustainability issues, and value add to the community in need.

Case Study (1): Floatable Toilet System in Cambodia

In this project, our students designed a toilet system that can float on water for a community-in-need in rural Cambodia, which was under threat of poor sanitary condition due to frequent floods in the region, using existing toilet systems which are very rudimentary. The students visited the village several times, the first of which is to speak to the villagers, where they also applied design thinking methodology in order to ascertain the villagers' needs. They then proceed with several iterations of the design back in Singapore and eventually developed a prototype that was tested in Cambodia. With the help of local craftsmen, the floatable toilet was largely constructed from bamboo, a locally available and renewable resource. Besides the floating structure, the team also designed a separation system that removes urine from faeces; an anaerobic digester to help convert the human waste into fertilizers, as well as a system to capture the biogas was produced to be used as fuel. Subsequent visits included gathering feedback from the villagers and making improvements to the system. They also include training for the villagers in using the new system.

Case Study (2): Rainwater Harvesting System in Nepal

In this project, our students introduced a rainwater harvesting system in Nagarkot, Nepal for a community of 300 children, aged between 4 to 14, and their teachers in a village school. The students applied design thinking methodology to first understand the needs of the community. The village is on a mountainous region and thus ground water is scarce. The main source of water is from rainfall and piped spring water from higher grounds. The villagers experience seasonal changes which greatly affect the supply of water and no water supply during dry season. In addition, there is an existing water tank, with a capacity of 7000 litres, at the village school. The tank stores piped spring water. Typically, everyone drinks straight from the tank and they may be susceptible to contamination of spring water that came from upstream. Through empathy studies and interviews with the local community, our students conceptualised several designs to provide clean and sustainable source of water while undertaking the Year 2 module. They also explored water purification processes to remove bacteria growth that will be evident in water stored over long periods of time.

Eventually, a team of students went back to Nagarkot to build the rainwater harvesting system with the aid of local community.

Case Study (3): Herbal Soap Production in India

In this project, our students developed a suitable formulation to produce herbal soap using locally available natural resources in Sikkim, India such as sunflower oil, coconut oil, mint and lemongrass. The Yuksam community in Sikkim planted and harvested cardamom to earn a living. A few years ago, a disease struck the cardamom plants and wiped out the entire plantation. The villagers suffered a massive loss of income. Through empathy studies and interviews with the local community, several ideas were conceptualised such as paper and soap making. After several rounds of communication with the local community, it was found that there was another organisation aiding them in a project involving paper making. Hence, our students embarked on soap making, developed a suitable formulation, renamed it as 'herbal soap' because it utilised plant-based ingredients. This project is still on-going. The next phase of this project is to explore sustainable processes and technology that is suitable to be implemented at Sikkim to produce the herbal soap in larger amounts.

CHALLENGES FACED

We faced several challenges in teaching of *Chemical Product Design and Development.* The three most significant ones are discussed in the paragraphs below.

Prototyping Chemical Products

Prototyping is often required in product design and development project. According to Ulrich and Eppinger (2008), prototypes are used for learning, integration, communication and milestones demonstration. Prototypes serve as learning tools because it demonstrations the workability of the product idea and to what extent it meets the user needs. Physical prototypes are much easier to understand than verbal description or sketch. Hence, they enrich communication with industry partners and users. Prototypes are also used to ensure that components and sub-systems of the product work together as expected. Comprehensive physical prototypes are most effective as integration tools in product development projects because they require the assembly and physical interconnection of all the parts and sub-assemblies that make up a product. In doing so, the prototype forces coordination between different members of the product development team. If the combination of any of the components of the product interferes with the overall function of the product, the problem may be detected through physical integration in a comprehensive prototype. Lastly, prototypes are used to demonstrate progress made by the team members and meeting various milestones.

A large variety of chemical product ideas are conceived by our students. Some are realizable and some are not. For prototypes that are easily constructed, the students create them in the workspaces provided by the polytechnic. For prototypes that required drilling and cutting that is beyond the works of the students, they are to seek assistance from skilled workers who are competent in handling powered tools and industrial size equipment. The skilled workers are usually not polytechnic staff and the students have to spend extra time and effort to source for such services.

Based on the prototypes, there are many which did not make it to the next stage of development. Therein lies the major challenges of introducing product design into chemical engineering curriculum. It had to be expected that not all ideas will translate into products; and not all products can be realized at diploma-level competency.

Students' Perception of Extending Work Done into Capstone Projects

A survey was conducted in 2010 when *Chemical Product Design and Development* (then known as *Product Design and Development*, or *PDD* in short) was first introduced into the DCHE curriculum. Among other questions, we asked students how comfortable they are in carrying on what they had done in the module to further the development work as their final year projects. We ask the following question:

> *Which of the descriptions below best describe your feeling towards executing a Final Year Project based on your own idea*? Tick (✓) **ONE** box only:
>
> ☐ Rejection – I'd rather do a project prescribed by the lecturer
>
> ☐ Indifferent – I am fine with either lecturer-prescribed project or my own project
>
> ☐ Mixed – Although I do look forward to carrying out my own project, I am somewhat worried if I can achieve what I set out to do
>
> ☐ Excited – I can't wait to realize my dream of doing my own project, regardless of the outcome whether I am successful or not
>
> ☐ Others – Please specify: ______________

The result is shown in Figure 4. Perhaps not surprisingly, many students (up to 51%) are rather apprehensive when it comes to continuing their work *as* their capstone projects. The reasons offered by students for expressing Rejection, Indifferent or Mixed feelings in their responses, are as follows in order of frequency of occurrence:

- Concern over workability of idea or concept proposed in *PDD*
- Lack of or no confidence that one is able to succeed
- Insufficient technical knowledge
- Play safe – own ideas not very good or too complicated, easier to focus if lecturer provide project
- Concern over outcome affecting cumulative GPA (Grade Point Average)
- *PDD* proposal lacked chemical engineering component
- View lecturer-proposed project as back-up in case *PDD* proposal fails
- Incompatible interest among group members
- Not enough time to explore further the idea in *PDD*

Although in subsequent years we had made various improvements to the module, especially with the introduction of more experimentation activities in year 1 for the module *Introduction to Chemical Product Design*, the reservation among students still ring true today. The concern over the heavy percentage the *Final Year Project* (8 credit units) contributed to the overall achievement in terms of GPA is very real indeed for the grade-conscious students, who feared that a dip in their GPA will compromise their chances of university admission.

It is also true that our students had not mastered all the various chemical engineering principles in Year 2 when they take the module *Chemical Product Design and Development*; as these core modules are being offered in the very same year of study. A survey of the various core chemical engineering modules also revealed the lack of worked examples in the area of chemical product design. The various tutorials in these core modules are provided to, firstly demonstrate the application of various engineering formula, and secondly in the design of process equipment such as pumps, heat exchangers, and separation columns. Kazerounian and Foley (2007) asserted that this lack of suitable examples on chemical product design can diminish students' ability to think creatively and/or critically. These authors maintained that creativity is possible for engineering students and had identified some barriers to creativity. Among these are: uncomfortable with ambiguity over the outcome, inability to keep an open mind when viewing a problem; and lack of inducement for creative behaviour, whether real or perceived. Although not explicitly mentioned by students in the survey, we believe these are some of the contributing factors.

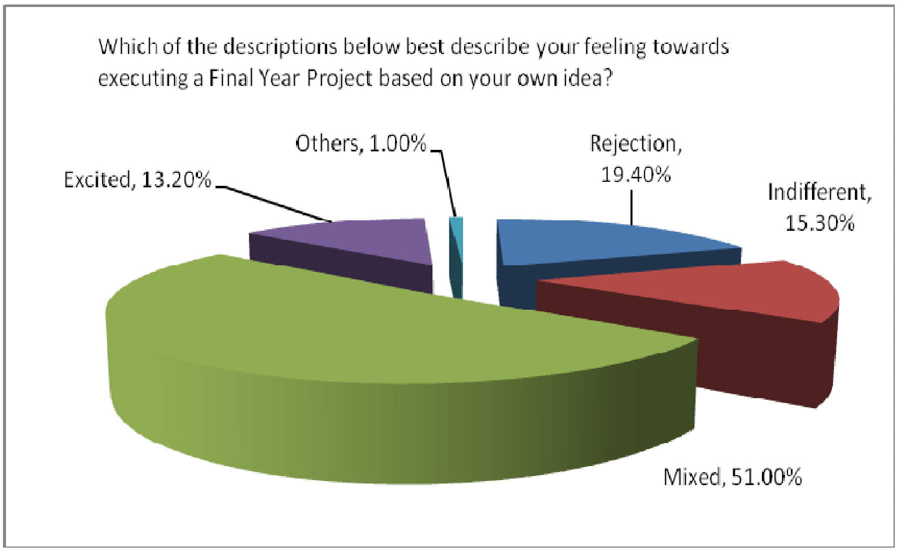

Figure 4. Attitude toward continuing *PDD* as *FYP*

Integrating Process and Product Designs

Currently, we faced difficulty in integrating process and product designs as one holistic project for our students. Process designs remain by and large an accreditation requirement of the Institution of Chemical Engineers, UK; which accredits our course.

As it is currently practiced in DCHE, process design involves the computer design (using simulation software) of chemical plant producing commodity chemicals. One downside is that such a simulated chemical plant will not really get built. On the other hand, our focus of chemical product design is often "systems" such as floatable toilet or rainwater harvesting systems as mentioned earlier as opposed to "products" as in formulations, ingredients, additives, etc. These chemical products "systems" do not quite meet the intended learning outcomes of process design and hence making real integration difficult. While we do have some final year projects that resulted in students producing "products" such as liquid detergent or biodiesel or low carbon footprint concrete mix, we are limited by time constraint in our *Final Year Project* to make any significant integration beyond requiring students to propose a plausible manufacturing scheme to scale-up production from the lab-scale to industrial-scale. This is limited to identifying the suitable processes and equipment (known as “unit operations” in chemical engineering parlance) and preparation of the corresponding process flow diagram. There would not be any simulation or modelling work.

MOVING FORWARD

We felt that there is a need to better manage the students’ expectations for capstone projects right at the beginning of the module *Chemical Product Design and Development*. We also need to review and revise our *Final Year Project* assessment scheme that emphasizes the “process outcome” rather than the “product outcome”. By “process outcome” we meant the assessment of students’ ability to use the various skills (such as ideation, idea selection, solution formulation and selection); and not the workability of the prototype or “final” product per se.

And as we gradually build up our own “collection” of chemical products, we can develop our own examples where chemical engineering principles can be applied in chemical product design and embed them into the teaching of the relevant core modules.

To-date, the percentage of students who truly want to further venture their work in *Chemical Product Design and Development* to capstone projects remains low. This is mainly because the students lack experience and knowledge in crafting the scope of the project. They also do not know as many academic staff and their area of expertise whom they can approach to seek advice and supervision. This is attributed to some academic staff only teach Year 3 modules. Thus, this is one area that the teaching team can improve to motivate more students to initiate capstone projects so as to encourage greater ownership by our students.

CONCLUSION

The Year-2 module *Chemical Product Design and Development* is an important “bridge” that connects the initial product conceptualization in year 1 until its eventual realization in year 3. Despite the fact that most students complain about too many assignments and tasks to be completed while undertaking the module, our students found that the *Chemical Product Design & Development* module enjoyable, interesting and extremely engaging because they become more familiar with the approach of design thinking, understand the usefulness of it and the process of learning became fun. Our students also realized that making a viable product is not an easy task, as well as them having to do much independent learning to acquire necessary skills. Having received both positive and negative feedback from students, the teaching team remains committed to meeting the challenges faced in providing meaningful learning experiences to all our students in the area of education as sustainable development.

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