SUSTAINABLE DEVELOPMENT IN CHEMICAL ENGINEERING CURRICULUM: REVIEW AND MOVING AHEAD

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ABSTRACT

The Diploma in Chemical Engineering (DCHE) introduced the teaching of chemical product design into its 3-year curriculum in 2009, which prepared the foundation for the subsequent integration of sustainable development into the curriculum. This paper presents a critical review of the changes in education for sustainable development (ESD) for the last 10 years, including the advent of Industry 4.0 and how it can impact ESD. The paper first outlines the general two-prong approach in DCHE, aimed at simultaneously satisfying the needs of the chemical processing industries for competent graduates, while at time same time made dual-use of available curriculum hours to enable students to use knowledge in chemical engineering to contribute to sustainable development using the CDIO Framework, with chemical products that meets the needs of the less-privileged at the bottom of the pyramid. The paper summarizes literature reviews of recent developments in ESD, why previous efforts did not lead to the desired results, as well as new challenges and opportunities afforded by Industry 4.0 technologies. The paper also discusses current view on sustainable development using a systems perspective; whereby sustainability is viewed as a dynamic system whose equilibrium is always disrupted. The framing on how ESD can be delivered also shifted towards a more transformative approach, by focusing on more on empowering the students, to prepare them in shaping their own views on the wicked nature of sustainability issues by taking into considerations the different and often-conflicting perspectives of various stakeholder, etc. An emerging approach in transformative learning is based on the theme of sustainability as a discourse. The paper then shares the findings from a recent survey of DCHE students on their learning experiences in chemical product design which had remain unchanged since the topic was introduced into the DCHE curriculum. The result showed that we had much to update in our approach to ESD in light of recent changes. The paper then presents an updated thinking on how DCHE can revised its coverage of sustainable development to move forward. The emphasis on teaching sustainable development is now directed towards preparing the learner, by equipping them with the knowledge, skills and attitudes that they need to negotiate and navigate the ever-changing sustainability landscape on their own. While retaining the same two-prong approach, the learning experiences will now be enhanced using the CDIO Framework to include competencies in using Industry 4.0 technologies in chemical processing as well as developing graduates with sustainable mindset who are able to contribute to sustainability well beyond their study in DCHE.

KEYWORDS

Sustainable Development, Chemical Engineering, Standards: 1, 2, 3, 5, 7, 9, 10, 11, 12

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". A teaching academic is known as a "lecturer", which is often referred to a as "faculty" in the universities.

INTRODUCTION

The Diploma in Chemical Engineering (DCHE) in Singapore Polytechnic (SP) is a 3-year course that aims to prepare graduates for the chemical processing industries, taking up various position as process technicians, engineering executives, technical support officers, etc. DCHE introduced its revised curriculum redesigned using the CDIO Framework for the first time in April 2008 and had been finetuning the course content ever since. DCHE added chemical product design and development into its curriculum in 2009, to broaden the application of chemical engineering principles in response to changing roles of chemical engineering in the 21st century, and to enhance the employment prospects of its graduates (Cheah & Ng, 2010). Recognizing the need to better prepare the students to be able to contribute positively to sustainable development, the curriculum was revised again in 2011 to emphasize chemical product design that focus on sustainability issues (Cheah, 2014; Yang & Cheah, 2014; Cheah, Yang & Sale, 2012). The enhancements include the adoption of design thinking (Cheah, 2012; Ng & Cheah, 2012) and the use of appropriate technology in students Final Year Project (Chua & Cheah, 2013). Readers interested in the design principles and pedagogical approach are encouraged to look at these earlier papers.

The approach taken in the abovementioned changes used a 2-prong strategy, aimed at making "double duty of teaching time" (Crawley et al, 2007) to maximize students learning not only in technical know-how, but also acquiring the skills needed and developing the right mindset and attitudes – the "dual impact learning". In short, the 2-prong strategy, designed using the CDIO Framework, resulted in an integrated curriculum with 2 pathways, one – termed the "chemical process pathway" that prepared students in chemical plant design and operations, and another – termed the "chemical product pathway" in chemical product design and development. For the latter, we introduced a project-spine in the curriculum, which consist of a basic-level design-implement experience in Year 1, and 2 modules in Semester 1 and Semester 2 of Year 2 respectively, that focused on chemical product design and development, with flexibility of allowing students to propose the types of project that they wanted to work on as their capstone in Year 3. DCHE students henceforth are required to complete 2 major projects in their year 3 of study: a chemical plant design project and a capstone project (based on chemical product design). Students learnt various chemical engineering principles that support both pathways. Figure 1 represents our approach to Education for Sustainable Development (ESD) using a project-spined that is sustainability-themed. And more recently, we also included the explicit teaching of self-directed learning skills in students, with the aim of making them more independent in their study, to prepare them to become lifelong learners (Cheah, 2019).

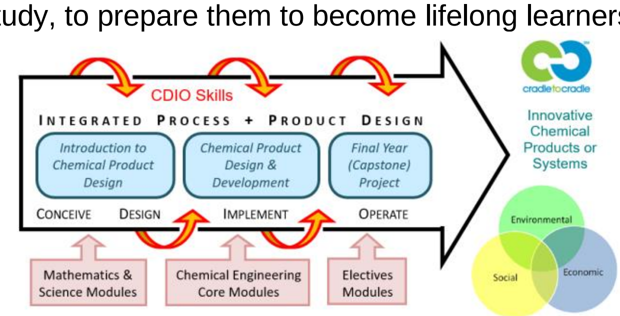

Figure 1. Integrated Curriculum for Chemical Product Design via Project-spine

As shown in Figure 1, various skills are also integrated and delivered via integrated learning experiences and active learning. The convergence came with the understanding that a chemical process can be designed to produce a particular chemical product. This is not realizable within the available curriculum hours for the design of specific process for the production of a specific product; so this topic was delivered to students via classroom lectures.

The objective is the dual outcomes of education, in that our students are able to: (1) use the learning gained to contribute professionally to their chosen discipline, to become valuable employees in the chemical processing industries who are competent in the workplace; and (2) use the same learning gained to contribute personally to efforts in sustainable development, to serve the broader needs of society, in particular to the less privileged at "at the bottom of the pyramid".

LITERATURE REVIEW: UPDATES IN ESD (INCLUDING IMPACT OF INDUSTRY 4.0)

Over the last 10 years, there had been major developments in the approaches to ESD. Questions had continually been raised on how much had ESD achieved in helping to meet the various objectives of the 17 UN Sustainable Development Goals (SDGs). A recent report from UNESCO summed up the findings: "……unfortunately not yet been possible to anchor sustainability in the teaching that occurs in higher education – apart from individual examples, such as Sweden, where higher education institutions are legally required to promote sustainable development" (UNESCO, 2017). Limitations of various approaches used had been highlighted, for example, over-emphasis of the use of technology (Segalas, et al, 2010) in particular had been overly focused on addressing environmental issues. Mochizuki (2019) noted that education often places emphasis on preparing students for competitive participation in the global economy, rather than to become critical and responsible members of society in alignment with the objectives of ESD. Alvarez & Rogers (2006) noted that much of what is going on in sustainability education is prescriptive, for example in establishing environmental targets, audits, energy and water efficiency. In these approaches, the roles and views of students are neglected, in particular any prior knowledge that they had, and tend to prescribe "a right position" to sustainability issues. Rather than utilizing the complexity of sustainability subject matter to support student thinking, sustainability is being utilized as an opportunity to maneuver students into one viewpoint or another (Scarff-Seatter & Ceulemans, 2017).

Increasingly, an emerging view is to look at sustainable development with a systems perspective (Lim et al, 2018; Zhang, et al, 2016): sustainability as a dynamic state that society is constantly trying to define and reach. Carew & Mitchell (2008) noted that understanding and identifying with a particular worldview among several should be seen as indicative of the contestability and complexity of sustainability studies. Kioupi & Voulvoulis (2019) suggested that sustainable development is to be considered as an end state: that the visions of an ideal, sustainable future as influenced by history and culture; where educational programs are indoctrination tools for achieving that kind of future. Sustainable society as a system state can only emerged as the result of complex interactions between system parameters and conditions with education guiding the transformational process for society in reaching such a dynamic state. The goal of higher education is now seen as supporting students in developing their capacity for recognizing and understanding the complexity of sustainability issues, and for thinking critically about assumptions, biases, beliefs, and attitudes while actively participating in their resolutions (Scarff-Seatter & Ceulemans, 2017). The aim of education would therefore be to prepare students who can: (i) develop sustainability attitudes, skills, and knowledge that inform decision making for the benefit of themselves and others, now and in the future; and (ii) act upon these decisions. In this view, students should no longer accepts any "uncritically assimilated explanation" by "experts" – rather, they are now seen as actors who can make their own choices and impact on sustainable development. Students should be allowed to make their own interpretations, rather than act on the "purposes, beliefs, judgments, and feelings of others" (Scarff-Seatter & Ceulemans, 2017). Students will be more open to and draw upon other views and possibilities: the "experience of seeing our worldview rather than seeing with our worldview" (Sterling, 2011). Such a learning is transformational in nature, involving perceptual change and coming to a transpersonal ethical and participative sensibility, or a shift towards a more relational way of seeing that inspires different values and practices.

To this end, transformational learning has therefore increasingly been conceptualized and operationalized in ESD (Aboytes & Barth, 2020; Laininen, 2019). Transformative learning evolved from the concept of perspective learning (Mezirow, 1978). According to Mezirow (2003), transformative learning is "learning that transforms problematic frames of reference – sets of fixed assumptions and expectations (habits of mind, meaning perspectives, mindsets) – to make them more inclusive, discriminating, open, reflective, and emotionally able to change". Several authors have elaborated the theory, but there is no uniform understanding of its content and no generally accepted definition for the concept (Laininen, 2019).

An outcome of transformative learning is that students developed "competence" to understand multiple ways of looking at the world, with an "ultimate goal" that integrates action into one's new view of the world; henceforth moving one towards a frame of reference that is more inclusive, discriminating, self-reflective, and integrative of experience. Sterling (2011) called such an approach as one that can "take us to the depth of things". We therefore decided on an ambitious (some may say audacious) goal of having our students develop a "sustainability mindset". Just like the words "sustainability" and "sustainable development", it can be used in multiple contexts. Kassel et al (2016) defined it as a way of thinking and being that results from a broad understanding of the ecosystem's manifestations, from social sensitivity, as well as an introspective focus on one's personal values and higher self, and finds its expression in actions for the greater good of the whole. Hermes & Rimanoczy (2018) identified 3 dimensions of sustainability mindset: systemic thinking, innovative thinking and being. In the context of ESD, it can be developed as a new lens through which individuals can look into the world, analyzing data and making better decisions.

To achieve the desire learning outcomes, Mezirow (1981) described the key characteristics of transformative learning in terms of learning processes (how people learn), outcomes (what they learn) and conditions (how to best support their learning). There has to be a shift in teaching practice, from teaching about sustainability as though it was fixed and definable, to a way of learning about the multiple ways in which sustainability is contested and understood. There also need to employ teaching approaches that go beyond the cognitive domains, to focus on the affective domain: values, attitudes and behaviours (Shephard, 2007). In addition, there also need to engage students in reflective practice (Balsiger, 2017). Correspondingly, there is also a need for change in the role of educators: Not to tell students what sustainability was or ought to be, but rather to develop within them the capacity to interpret what it might be.

Over this period, the emergence of the so-called Fourth Industrial Revolution or Industry 4.0 is also driving changes not only in the manufacturing sector, but also in education, including ESD. However, one must note that the very notion of Industry 4.0 did not start with sustainable development: it has always been about improving productivity of manufacturing by leveraging on various technological advancement, e.g. Internet of Things, Big Data, Cloud Computing, Cyber-Physical System, etc. Knudsen & Kaivo-oja (2018) noted that although Industry 4.0 and its related technologies may facilitate more sustainable production, but sustainability is not an endogenous feature of Industry 4.0. Anadon, et al (2016) called for the need to make

technological innovation work explicitly for sustainable development. While some authors spoke on the opportunities afforded by Industry 4.0 on sustainable development (e.g. Ordieres-Meré, et al 2020; Klymenko, et al 2019), others such as Kohtala (2015) noted that these are not a given, that there will be new, clearly cleaner production paradigm.
There are positive findings reported on how Industry 4.0 can contribute to sustainable development, but the transition to Industry 4.0 does not automatically leads to sustainable development. Equally there are reports of negative impacts, that increased technology update can also happen unsustainably. Olav, et al (2020) for example, summarised reports from various sources on the positive impact of how Industry 4.0 added values to consumers (better experience, enhanced customization, reduced cost) as well as to companies (improved efficiency, boosted synergy). On the other hand, Bonilla, et al (2018) reported on findings from various studies of the negative impacts of various elements of industry 4.0 (automation, integration, digitization) on the environment. Ally & Wark (2019) noted that little research has been done on the short- or long-term consequences of applying Industry 4.0 technologies in practice. Kiron & Unruh (2018) called the convergence of digitalization and sustainability as leading to the "perfect transformative storm".

REFLECTION ON WORK DONE: SURVEY OF STUDENT EXPERIENCE IN ESD

The current approach to ESD based on Figure 1 had been running since its introduction into the DCHE curriculum in 2011. This model of execution had remained largely unchanged and after the initial surveys where sustainable development was introduced (the findings of which are presented in earlier works: see Cheah, Yang & Sale, 2012; Chua & Cheah, 2013), students were no longer asked on how they find learning about ESD in this manner. From 2015 onwards, the entire teaching team, are all caught up in other initiatives such as responding to changes brought on by Industry 4.0 (e.g. Yang & Cheah, 2020; Cheah & Yang, 2018) and changing students' dispositions necessitating the use of different approach to teaching and learning such as flipped classroom (e.g. Sale & Cheah, 2017; Cheah & Sale, 2017; Cheah, Sale & Lee, 2016). There is also a new initiative to make students more self-directed in managing their own learning (Cheah, 2020; Cheah, Wong & Yang, 2019). All these works inevitably resulted in a certain degree of 'neglect" of ESD; as every module coordinator try to cope with the more immediate changes affecting his/her modules.

To catch up on our students' learning experience in ESD, in particular in light of the recent developments in ESD, in September 2020 and February 2021 we conducted a brief survey on 2 cohorts of our Year 3 students (each about 60 students) on how they perceived ESD over the 3 years of studying chemical engineering in SP. The survey is administered over and above other surveys students are asked to complete, at both institutional level as well as national level mandated by the Ministry of Education of Singapore. This arises from the unprecedented Covid-19 pandemic, affecting student learning due to campus closure (complete or partial; depending on which point in time). To minimize student "survey fatigue" we kept the questions on ESD to a minimum to make room for other questions within the same set of questionnaire.

The questions on ESD and student responses (total 70) are shown in Figures 2 to 5. It can be seen that our students acknowledged the importance of sustainable development (Figure 2, with average score of 8.56) and a large percentage of them (48.57% who indicated 'to a moderate extent' and 27.14% who indicated 'to a good extent') are able to make use knowledge in chemical engineering to contribute towards sustainable development (Figure 3). On the other hand, it is clear that not all our Capstone projects are sustainability-themed

(Figure 4) due to the fact that we also take on some industry-sponsored projects the scope of which are already defined by the companies. Also, the extent to which sustainability elements are included also depends on how the project is scoped. It is heartening to see some students reported that they see opportunities for their projects to be linked to sustainable development even though this aspect is not part of the project scope (Figure 3). Overall, the majority of students still reported that they are satisfied with the coverage of sustainable development in the curriculum (Figure 5).

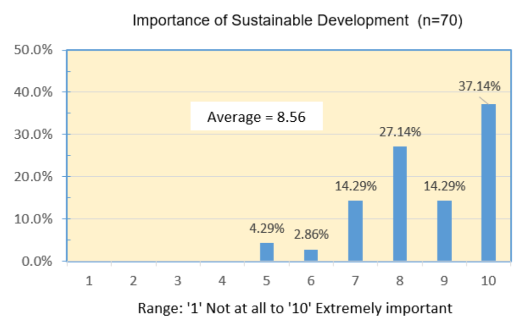

Figure 2. Importance of Sustainable Development

Q1. This question pertains to modules that cover chemical engineering core principles such as fluid transfer, heat transfer, separation processes, process instrumentation and control, and chemical reaction engineering. It does NOT include modules on chemical product design. To what extent do you think DCHE had prepared you to contribute to sustainable development? Choose ONE that best matches your perception.

(a) Not at all - I don't recall I've been taught anything on sustainable development

(b) To a limited extent - I have some ideas on sustainable development but don't know how to use what I learnt

(c) To a moderate extent - I can see how some of the core principles taught can be applied in sustainable development

(d) To a good extent - I believe I am able to use these core principles that I have learnt for matters related to sustainable development.

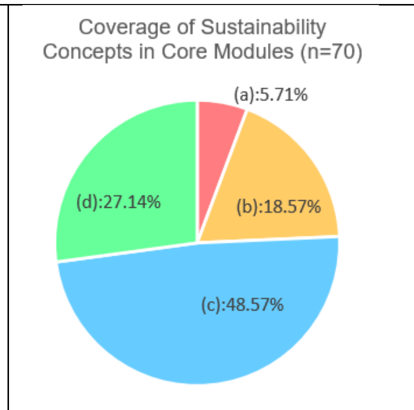

Figure 3. Coverage in Core Modules (not including modules in project spine)

Q2. Is your FYP related to sustainable development? Choose ONE that best match your experience from completing the FYP.

(a) Not at all

(b) Maybe. I am not sure. It is not clear to me

(c) Yes, but only a limited extent: it has application in sustainable development, but I am not working on that aspect

(d) Yes, to some extent. Some aspects of it has applications in sustainable development.

(e) Yes, my FYP it is all about sustainable development.

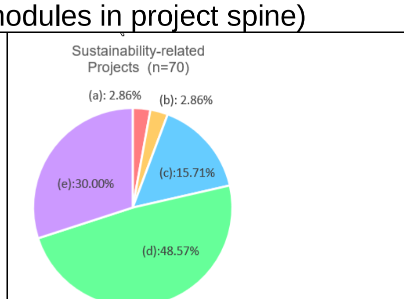

Figure 4. FYP with elements of Sustainable Development

Q3.Overall, in relation to your answer to Question 1 on importance of sustainable development to chemical engineering, are you satisfied with the coverage of sustainable development in the DCHE curriculum? Choose ONE that more represent your sentiment.

(a) Not satisfied at all

(b) Not very satisfied

(c) Somewhat satisfied

(d) Satisfied

(e) Very satisfied

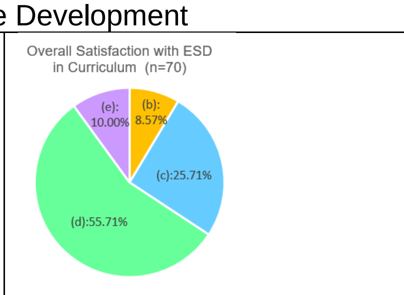

Figure 5. Overall Satisfaction with ESD in DCHE Curriculum

Reflecting on our effort over the past 10 years, we can modestly claim that we had had some success at instilling a “can do” spirit among our students: by building on their intrinsic motivation, we had given our students the confidence to make a difference using the knowledge that they gained. We therefore conclude that the approach we put in place for the “dual pathway” is working; and identified several shortcomings that need to be addressed. There is still a significant number of students (5.71%) who reported that they did not see how sustainability had been covered in the various core modules (Figure 2). Also a significant number (18.57%) reported that they do not know how to use what they learnt (Figure 3). Lastly, there is still a small number of students (2.86%) being not very sure if their project is related to sustainability (Figure 4). When compared to our initial aim at integrating sustainable development into the DCHE curriculum, the results showed that we had fallen short. Our aim then is to strive to achieve what is termed as “third-order learning or transformative learning” (Sterling, 2004) as shown in Table 1.

Table 1. Three Levels of Education in relation to Sustainability

Education about sustainability	First-order learning Emphasis is on content/knowledge-based learning within the dominant paradigm Assumes that meaning of sustainability can be clearly identified and taught as a separate subject Essentially ‘learning as maintenance’ of current paradigm
Education for sustainability	Second-order learning Emphasis is on ‘learning for change’ that includes content, but goes further to include values and capability bias Deeper learning: involves critical and reflective thinking about sustainability Assumed that we know clearly what values, knowledge and skills ‘are needed’ for change and while challenging the existing paradigm leaves it mainly intact
Education as sustainability (Sustainable Education)	Third-order, transformative learning Emphasis is on process and quality of learning, which is seen as an essentially creative, reflective and participative process Knowing is seen as approximate, relational and provisional, and learning is continual exploration through practice Shift is towards ‘learning as change’ which engages the whole person and learning institution Process of sustainable development or sustainable living is essentially one of learning, while context of learning is essentially that of sustainability

What we can conclude from our efforts at ESD to date, is that we have yet to achieve the transformative learning that we aspire. At best, we just reached the lower “threshold” of second-order learning, meaning that our approach to ESD had met some elements of second-order learning, but had not fully embraced what it entailed. Falling short for example is reflective thinking about sustainability. We do not make is an explicit requirement that students in such practice as part of their capstone project work. There is also no explicit effort in discussing the needed values for transformative change. We are still locked in existing paradigm. As noted by Sterling (2011), learning that took place within an existing paradigm does not change the paradigm, whereas learning that facilitates a fundamental recognition of paradigm and enables paradigmatic reconstruction is by definition transformative. There are more to be done.

MOVING AHEAD: IMPROVING ESD IN CHEMICAL ENGINEERING CURRICULUM WHILE MAINTAINING THE DUAL PATHWAYS

There is a need to have renewed efforts aimed at raising greater awareness among students on various issues related to sustainable development, to promote a stronger 'bias-for-action' among students. Aboytes & Barth (2020) noted that if used appropriately, transformative learning can contribute to the design and implementation of educational interventions and assessments of learning towards sustainability. We are now in the process of revisiting the CDIO Framework to work out the required competencies in particular the affective domain. The aim is to reinforce current approach of learning via projects supported by other modules (Figure 1) to develop new competencies required for Industry 4.0 and ESD.

This requires us to go beyond the typical integration of skills widely covered in our integrated curriculum such as Teamwork and different forms of Communication, namely oral, written and graphical. We need to strengthen existing coverage of CDIO Syllabus Part 2.3 *Systems Thinking* and Part 4.1.6 *Developing a Global Perspective*; as well as other aspects of Communication that includes 3.2.7 *Inquiry, Listening and Dialog*; 3.2.8 *Negotiation, Compromise and Conflict Resolution*; and 3.2.9 *Advocacy*. We also need to also include other personal and professional skills and attributes that, to date, received little attention. These include Part 2.4 *Attitudes, Thoughts and Learning* (for example 2.4.1 *Initiative and Willingness to Make Decisions in the Face of Uncertainty*; 2.4.*2 Perseverance, Urgency and Will to Deliver, Resourcefulness and Flexibility*) and Part 2.5 *Ethics, Equity and Other Responsibilities* (for example 2.5.1 *Ethics, Integrity and Social Responsibility*; and 2.5.5 *Equity and Diversity*).

These parts of the CDIO Syllabus will serve as learning outcomes to be mapped to the skill sets required for Industry 4.0 and sustainability mindset. This will then guide the redesign of our integrated curriculum, integrated learning experiences, learning assessment, faculty teaching competency and program evaluation. In our context, for skills and attributes required for Industry 4.0, we took reference from the Singapore Skills Framework, which are captured in 16 critical core skills (Mercer & SSG, 2020). For sustainability mindset, the approach of sustainability as a discourse shall be used, and students can be engaged in discussing about sustainable development in the context of chemical engineering. Ideas for chemical products can be tied explicitly to addressing one (or more) of the 17 Sustainable Development Goals (SDGs). In all these endeavours, skills and attitudes associated with the affective domain as mentioned in the previous paragraph can be integrated, over several stages of study to the required proficiency level consistent with DCHE's spiral curriculum course structure (Cheah & Yang, 2018). Detailed discussion of these works is beyond the scope of this paper and will be shared at future conferences. An example of our approach will be provided in the subsequent paragraphs.

More specifically for ESD, we shall adopt the approach to transformative learning by Scarff-Seatter & Ceulemans (2017) who position it as a process that:

(i) allows students to question taken for granted frames of reference to become more discriminating, open, and reflective
(ii) produces major changes in thinking, feeling, acting, relating, and being
(iii) allows for evaluating values and assumptions for their effectiveness towards shared goals

With regards to how best to support students in their learning, we will adopt the approach suggested by the same authors (Scarff-Seatter & Ceulemans, 2017) to treat *sustainability as a discourse*; referring to sustainability issues as a contested discourse that is spoken and claimed by competing groups and cultures, rather than a concept that can be pinned down and identified in the real world. This approach is in line with our dual outcome approach to education alluded to in the earlier paragraph. We remain committed to prepare our students for the profession and industry they are trained for, while at the same time, equip them with the mindset that allows them to resolve any “dissonance” (Kagawa, 2007) in the sustainability issues that they are facing.

The author opined that the topics that can lend themselves easily for this approach shall be those that posed the most controversies, i.e. “wicked problems” (Ritter & Webber, 1973). Such issues has the following characteristics: incomplete or contradictory data/information, many stakeholders with different interests and opinions, interconnected, and costly to resolve. To illustrate the proposed approach, we shall use the ‘classical’ debate of food vs. fuel, which from the point of view of sustainable development goals, can involve Goal No.1 *No Poverty*, Goal No.2 *Zero Hunger*, Goal No.7 *Affordable and Clean Energy*, and Goal No.15 *Life on Land*. The 2 skills that we will use to illustrate our approach are "sense-making" (described as “leverage sources of qualitative and quantitative information and data to recognise patterns, spot opportunities, infer insights and inform decisions”) and “digital fluency” (described as “leverage digital technology tools, systems, and software across work processes and activities to solve problems, drive efficiency and facilitate information sharing”). They are chosen because they are applicable to both Industry 4.0 and sustainable development, and also able to support the attainment of learning outcomes identified earlier, e.g. CDIO Syllabus Parts 2.4 and 2.5. These 2 skills are complementary in nature and should be taught simultaneously, and progressively developed using the DCHE spiral curriculum course structure. The availability of massive amounts of data arising from adoption and implementation of Industry 4.0 technologies (e.g. smart sensors) means that both engineers and technicians must be able to make sense of what all these data implied. They must also possess the right data handing skills, such as data manipulation, validation and visualization to gain useful insights from the data for decision-making.

Both sense making and digital fluency can be contextualized and integrated into the DCHE curriculum straight from Year 1 Semester 1. For example, in the module *Introduction to Chemical Engineering,* students can be taught to use sense making skill in discussing about food vs fuel, for example in understanding different perspectives from various stakeholders, in discerning claims or counterclaims from both proponents and opponents in the debate. They can also learn about data manipulation and visualization, from experimental works in the module *Laboratory and Process Skills 1*. Moving on to Year 1 Semester 2, they can hone their data management skills, this time focusing on data validation of their experimental results in the module *Laboratory and Process Skills 2*. They can learn about the efficacy of biofuel production from different sources (for example, via seeds or nuts) in *Chemical Engineering Thermodynamics*. Then, in Year 2 Semester 1, students will take the module *Introduction to Chemical Product Design*, where they can look deeper some published figures of food price index, biofuel prices, etc as part of literature review on the impact of their proposed chemical product. This can be further reinforced in Year 2 Semester 2 in the module *Chemical Reaction Engineering*, where students can be engaged in further discussion on the role of technology in addressing the issue, e.g. improving the yield of food crop or greater conversion of biofuel. This in turn can impact the design choices in Year 2 Semester 2 module *Chemical Product Design and Development*. In addition, students also learn the operation of various pilot plants in the Year 2 modules *Process Operation Skills 1* and *Process Operation Skills 2*; whereby they need to make sense of the data generated from the plants from the various smart sensors and instruments. These modules are also mutually supportive of 2 other core modules, *Separation Processes and Simulation* and *Chemical Engineering Design Calculations*. Discussions on sustainability issues can be bult into the learnings, via case studies for example the necessity of fuels to enable chemical plant operations on one hand, and flaring (i.e. burning off) of excess gases produced during plant operation vs. recovery of these gases as fuel. This is then enhanced by integration of Industry 4.0 technologies that makes use of data analytics to look at sources of fuel consumption vs generation to improve plant operation. The ‘convergence’ come in the form of plant design project that students need to complete is Year 3, which is from the module *Plant Design, Economics and Sustainable Development* and final year *Capstone Project*. The former is positioned to develop students as professionals needed by the chemical industries, with sustainability mindset to better understand the impact of technological developments on plant operation from a sustainable development perspective, vis-à-vis their roles and responsibilities as a chemical engineer or technician. In this manner, they can develop to become useful individual with sustainability mindset that allows them to negotiate and navigate the sustainable development landscape (as a dynamic system) that continues to unfold, well beyond their study in SP, to contribute positively to sustainability.

Lastly, in order to deliver the redesigned curriculum, one main key challenge is how to train lecturers to facilitate the discussion that is required using sustainability as a discourse, along with the assessment of the attainment of the desired learning outcomes. As noted by Lange (2004), sustainability education is not easy and few educators have training in how to do it, primarily due to its interdisciplinary nature (e.g. social sciences, psychology, etc), which is uncomfortable for lecturers. We need to carry out further research into this area, in order to prepare suitable professional development programs for our lecturers.

CONCLUSION

This paper provides a quick review of the recent ESD landscape that help shaped the approach to improve the integration of sustainable development in the chemical engineering curriculum, while simultaneously also addressed the curricular changes needed to better prepare our students for the post-Industry 4.0 working environment. The approach sets a high bar that aimed to develop sustainable mindset among students, using transformative learning. This will done through strengthening the current approach that maximize available curriculum hours to simultaneously develop competencies need for both Industry 4.0 and sustainable development, by identifying skill sets common for both. An example of such “dual impact learning” can be achieved using sense making and data fluency is shared. Much work remains to be done. However, we remained optimistic that the thoughtful application of the CDIO Framework will provide the necessary guidance need to navigate such a challenging endeavour.

REFERENCES

Aboytes, J.G.R. & Barth, M. (2020). Transformative Learning in the Field of Sustainability: A Systematic Literature Review (1999-2019), *International Journal of Sustainability in Higher Education*, Vol.21, No.5; pp.993-1013

Ally, M. & Wark, W. (2019). Learning for Sustainable Development in the Fourth Industrial Revolution, *Proceedings of the 9th Pan Commonwealth Forum*, September 9-12; Edinburgh, Scotland

Alvarez, A. & Rogers, J. (2006). Going "Out There": Learning about Sustainability in Place, *International Journal of Sustainability in Higher Education*, Vol.7, No.2, pp.176-188

Anadon, L.D., Chan, G., Harley, A.G., Matus, K., Moon, S., Murthy, S.L. & Clark, W.C. (2016). Making technological innovation work for sustainable development, *Proceedings of the National Academy of Sciences*, Vol.113, No.35, 9682-9690

Balsiger, J., Förster, R., Mader, C., Nagel, U., Sironi, H., Wilhelm, S. & Zimmermann, A.B. (2017). Transformative Learning and Education for Sustainable Development, *GAIA*, 26(4), pp.357-359

Bonilla, S.H., Silva, H.R.O., da Silva, M.T., Goncalves, R.F. & Sacomano, J.B. (2018). Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges, *Sustainability*, *10*(10), 3740; doi.org/10.3390/su10103740

Carew, A., & Mitchell, C. (2008). Teaching Sustainability as a Contested Concept: Capitalizing on Variation in Engineering Educators' Conceptions of Environmental, Social, and Economic Sustainability, *Journal of Cleaner Production*, 16, pp.105-115

Cheah, S.M. (2020). Case Study on Self-Directed Learning in Year 1 Chemical Engineering, *Proceedings of the 16th International CDIO Conference (hosted ONLINE by Chalmers University of Technology)*, June 8-11; Gothenburg, Sweden

Cheah, S.M., Wong, Y. & Yang, K. (2019). A Model to Explicitly Teach Self-Directed Learning to Chemical Engineering Students, *Proceedings of the 15th International CDIO Conference*, June 24-28; Aarhus, Denmark

Cheah, S.M. (2019). Teaching Students Self-Directed Learning to Support Education for Sustainable Development, *Proceedings of the* 13th *International Symposium on Advances in Technology Education* (ISATE), September 17-20; Tokuyama, Japan

Cheah, S.M. & Yang, K. (2018). CDIO Framework and SkillsFuture: Redesign of Chemical Engineering Curriculum after 10 Years of Implementing CDIO, *Proceedings of the 14th International CDIO Conference*, June 28-July 2; Kanazawa, Japan

Cheah, S.M. & Sale, D. (2017). Pedagogy for Evidence-based Flipped Classroom – Part 2: Case Study, *Proceedings of the 13th International CDIO Conference*, June 18-22; Calgary, Canada

Cheah, S.M., Sale, D. & Lee, H.B. (2016). Flipping a Chemical Engineering Module using an Evidence-based Teaching Approach, *Proceedings of the 12th International CDIO Conference*, June 12-16; Turku, Finland

Cheah, S.M. (2014). CDIO as Curriculum Model for Education for Sustainable Development, *Proceedings of the* 10th International CDIO Conference, June 15-19; Barcelona, Spain

Cheah, S.M. (2012). Learning Points from Executing a Final Year Project Enhanced with Design Thinking, *Proceedings of the* 6th *International Symposium on Advances in Technology Education* (ISATE), September 19-21; Kitakyushu, Japan

Cheah, S.M. & Ng, H.T. (2010). Product Design and Development for Chemical Engineering: Issues and Challenges, *Proceedings of the 6th International CDIO Conference*, June 14-18; Montreal, Canada

Cheah, S.M. & Yang, K. (2018). CDIO Framework and SkillsFuture: Redesign of Chemical Engineering Curriculum after 10 Years of Implementing CDIO, *Proceedings of the 14th International CDIO Conference*, June 28 – July 2; Kanazawa, Japan

Cheah, S.M., Yang, K. & Sale, D. (2012). Pedagogical Approach to Integrate Sustainable Development into Engineering Curriculum, *Proceedings of the* 8th *International CDIO Conference*, July 1-5; Brisbane, Australia

Chua, P.H. & Cheah, S.M. (2013). Education for Sustainable Development using Design Thinking and Appropriate Technology, *Proceedings of the* 9th *International CDIO Conference,* June 10-13; Cambridge, Massachusetts, USA

Crawley, E.F., Malmqvist, J., Ostlund, S. & Brodeur, D.R. (2007). *Rethinking Engineering Education – The CDIO Approach*, Springer: Science+Business Media LLC

Hermes, J. & Rimanoczy, I. (2018). Deep Learning for a Sustainability Mindset, *International Journal of Management Education*, Vol.16, pp.460-467

Kagawa, F., (2007). Dissonance in Students' Perceptions of Sustainable Development and Sustainability: Implications for Curriculum Change, *International Journal of Sustainability in Higher Education*, Vol.8, pp.317-338

Kassel, K., Rimanoczy, I., & Mitchell, S. (2016). The Sustainability Mindset: Connecting Being, Thinking and Doing in Management Education, *Proceedings from 76th Annual Meeting of the Academy of Management,* Anaheim, CA.

Kioupi, V. & Voulvoulis, N. (2019). Education for Sustainable Development: A Systemic Framework for Connecting the SDGs to Educational Outcomes, *Sustainability*, 11, 6104; doi:10.3390/su11216104

Kiron, D. & Unruh, G. (2018). The Convergence of Digitalization and Sustainability, *MIT Sloan Management Review*, https://sloanreview.mit.edu/article/, [accessed Dec 9, 2020]

Klymenko, O., Halse, L.L., Jaeger, B. & Nerger, A.J. (2019). Digitalization and Environmental Sustainability: What are the Opportunities, 26th EurOMA Conference, June 19-19, Helsinki, Finland

Knudsen, M.S. & Kaivo-oja, J. (2018). Bridging Industry 4.0 and Circular Economy: A New Research Agenda for Finland?, https://ffrc.wordpress.com/2018/09/12/bridging-industry-4-0-and-circular-economy/ [accessed August 5, 2020]

Kohtala, C. (2015). Addressing Sustainability in Research on Distributed Production: An Integrated Literature Review, *Journal of Cleaner Production*, Vol.106, pp.654-68
Laininen E. (2019). Transforming Our Worldview Towards a Sustainable Future, in *Sustainability, Human Well-Being, and the Future of Education*, Cook J. (eds); Palgrave Macmillan
Lange, E.A. (2004). Transformative and Restorative Learning: A Vital Dialectic for Sustainable Societies, *Adult Education Quarterly*, 54, pp.121-139
Lim, M.M.L., Søgaard Jørgensen, P. & Wyborn, C.A. (2018). Reframing the Sustainable Development Goals to Achieve Sustainable Development in the Anthropocene – A Systems Approach, *Ecology and Society* , 23(3):22
Mercer & SSG (2020). Critical Core Skills that Matter in a Post-COVID World, webinar presented on August 27, 2020; Singapore
Mezirow, J. (1978). Perspective Transformation, *Adult Education Quarterly*, 28(2), pp.100-110
Mezirow, J. (1981). A Critical Theory of Adult Learning and Education, *Adult Education Quarterly*, 32(1), pp.3-24
Mezirow, J. (1998). On Critical Reflection, *Adult Education Quarterly*, 48(3), pp.185-198
Mezirow, J. (2003). Transformative Learning as a Discourse, *Journal of Transformative Education*, Vol.1, No.1, pp.58-63
Mochizuki, Y. (2019). Rethinking Schooling for the 21st Century: UNESCO-MGIEP's Contribution to SDG 4.7, *Sustainability: The Journal of Record*, Vol.12, No.2, pp.88-92
Ng, H.T. & Cheah, S.M. (2012). Chemical Product Engineering using CDIO Enhanced with Design Thinking, *Proceedings of the* 8th *International CDIO Conference*, July 1-5; Brisbane, Australia
Ordieres-Meré, J., Remón, T.P & Rubio, J. (2020). Digitalization: An Opportunity for Contributing to Sustainability from Knowledge Creation, *Sustainability*, 12, 1460; doi.org/10.3390/su12041460
Olah, J., Aburumman, N., Popp, J., Khan, M.A., Haddad, H. & Kitukutha, N. (2020). Impact of Industry 4.0 on Environmental Sustainability, *Sustainability*, 12, 4674; doi.org/10.3390/su12114674
Rittel, H.W.J. & Webber, M.M. (1973). Dilemmas in a General Theory of Planning, *Policy Sciences*, Vol.4; pp.155-169
Sale, D. & Cheah, S.M. (2017). Pedagogy for Evidence-based Flipped Classroom – Part 1: Framework, *Proceedings of the* 13th International CDIO Conference, June 18-22; Calgary, Canada
Scarff-Seatter, C. & Ceulemans, K. (2017). Teaching Sustainability in Higher Education: Pedagogical Styles that Make a Difference, *Canadian Journal of Higher Education*, Vol.47, No.2, pp.47-70
Segalàs, J., Ferrer-Balas, D. & Mulder, K. (2010). What do Engineering Students Learn in Sustainability Courses? The Effect of the Pedagogical Approach, *Journal of Cleaner Production*, 18(3), pp.275-284
Shephard, K. (2008). Higher Education for Sustainability: Seeking Affective Learning Outcomes, *International Journal of Sustainability in Higher Education*, Vol.9(1), pp.87-98
Sheppard, K. & Gallois, B. (1999). The Design Spine: Revision of the Engineering Curriculum to Include a Design Experience Each Semester, *Proceedings the 106th ASEE Annual Conference & Exposition*, June 20-23; Charlotte, North Carolina, USA
Sipos, Y., Battisti, B. & Grimm, K. (2008). Achieving Transformative Sustainability Learning: Engaging Head, Hands and Heart, *International Journal of Sustainability in Higher Education,* Vol.9, pp.68-86
Sterling, S. (2011). Transformative Learning and Sustainability: Sketching the Conceptual Ground, *Learning and Teaching in Higher Education*, Vol.5; pp.17-33
Sterling, S. (2004). Higher Education, Sustainability, and the Role of Systemic Learning. *Higher Education and the Challenge of Sustainability: Problematics, Promise and Practice*, Corcoran, P.B. and Wals, A.E.J. (Eds.), Kluwer: Dordrecht, pp.47-70
UNESCO (2017). *A Decade of Progress on Education for Sustainable Development*, Michelsen, G. & Wells, P.J. (Eds), United Nations Educational, Scientific and Cultural Organization
Van Poeck, K., Læssøe, J. & Block, T. (2017). An Exploration of Sustainability Change Agents as Facilitators of Non-formal Learning: Mapping a Moving and Intertwined Landscape, *Ecology and Society*, 22(2):33
Yang, K. & Cheah, S.M. (2020). Inculcating Safety Mindset in Chemical Engineering Students using AR/VR, *Proceedings of the 16th International CDIO Conference (hosted ONLINE by Chalmers University of Technology)*, June 8-11; Gothenburg, Sweden
Yang, K. & Cheah, S.M. (2014). Chemical Product Design as Foundation for Education as Sustainable Development, *Proceedings of the 10th International CDIO Conference*, June 15-19; Barcelona, Spain

Zhang, Q., Prouty, C., Zimmerman, J.B. & Mihelcic, J.R. (2016). More than Target 6.3: A Systems Approach to Rethinking Sustainable Development Goals in a Resource-Scarce World, *Engineering*, Vol.2, pp.481-489

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