CHEMICAL ENGINEERING EDUCATION: PEDAGOGY FOR LEARNING FROM FAILURE IN PROCESS PLANT OPERATIONS

Sin-Moh CHEAH

School of Chemical & Life Sciences, Singapore Polytechnic

ABSTRACT

The aim of this paper is to propose a pedagogy based on learning from failure to develop the confidence and competency that graduates from the Diploma in Chemical Engineering needed to function effectively in their job role as process technicians in the chemical processing industries. It is further suggested that the CDIO Framework can be used to achieve this aim. The paper first highlights the danger of losing vital cognitive skills due to increased automation and digitalization; and also explains the limitation of learning using simulations, despite these being the most dominant way of preparing students for work. Next, it introduces the concept of learning from failure; and argued that the prevailing approach of “Learning from Accidents” is not always effective, especially when one lacks the necessary scientific knowhow and understanding of complexities of issues involved. The modular way of teaching, where different engineering fundamentals (e.g. fluid flow, heat transfer, etc) are taught in separate modules by different lecturers, often resulted in the opposite outcome: “designing out failure”. Problem solving often means working through questions that focus on applying the correct equations within the confine of the respective module; often neglecting the need to use valid data. Students are not taught to integrate the knowledge until later year of study by creating a computer model of a chemical plant. This paper then suggests a pedagogy for learning from failure that can be formulated to sensitize students to the notion of failure as a form of learning, rather than as an outcome to be avoided. In the context of chemical plant operation, this means that one must be able to make sense of big data, notably the relationships between process variables in plant operations. This will address the issue of “unknown knowns”, referring to situations where students were unable to see the connections between knowledge learnt from different modules in problem analysis. This paper illustrates how the CDIO Framework, along with a set of principles for learning from failure, can be used to design an integrated curriculum that progressively develop a new “failure-tolerant” mindset, using integrated learning experiences infused with “deliberate failure” to scaffold learning in process plant operations. Such learning can start with students being aware of interdependencies of various process variables, moving on to interactions between different plant equipment during operation. This paper concludes with discussion on how such new mindset can be further developed using the pedagogy presented.

KEYWORDS

Learning from Failure, Digitalization, Chemical Engineering, CDIO Core Standards 1, 2, 3, 7.

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 CONTEXT

Today’s education is struggling to keep up with changes, mostly notably brought about by the Fourth Industrial Revolution, Sustainable Development and Globalization. This is particularly true for engineering education, due not only to technological advances but also because of the increasing need to include learning from other disciplines such as humanities and the arts; all the while still having to retain the basic scientific principles and engineering fundamentals. Gajek, et al (2022) suggested that the main future competencies required for the training of chemical engineers in relation to Industry 4.0 technologies are digital competences (process software and system safety, ability to handle IT security and safety), soft competences (with culture, leadership, communication and organization) and the business or management competences, such as decision-making, complexity). In short, skills and attitudinal aspects are increasing need to be integrated into an already-packed curriculum to provide the suitable context for learning. Digital competencies in particular, is now a priority area in chemical engineering education (Zandi, et al, 2022). This often begs the question: What are the “fundamentals of fundamentals” that students need to know, as far as technical knowledge is concerned, to remain competent, and confident in tackling workplace issues?

The chemical processing industry is a high-risk one: it often deals with materials that are toxic and flammable, under conditions of high pressure and temperature. Advances in technologies had resulted in more integrated chemical plants and had over the years, made the operation safer. Ironically, this means that the probabilities or likelihood of an incident happening is low; but the consequences will be very high should one occurred. Moreover, there is no way to eliminate risk completely. Hence, it is of paramount importance that employees are effectively trained to respond to process plant upsets in a timely manner; to take proper corrective actions to prevent escalation of the situation. A process may spin out of control, leading in loss of containment that can result in toxic and/or flammable releases, fires and explosions.

This paper specifically explored the area of chemical processing plant operations in the age of digitalization, characterized by availability of big data; and the need to make sense of these data for better decision-making. Use of machine learning (ML) such as neural networks coupled with artificial intelligence (AI) will enable the rapid processing of large big data fed by numerous sensors, execution of pre-programmed algorithms, and displaying the status of the plant in real time on dashboards.

This paper stressed the importance of better preparing our students so that they are not only technically competent but more importantly, confident in interpreting these data especially during process plant emergencies. The efficiency of the ML/AI system will put the deluge of data through pre-programmed diagnostics, offer possible causes and recommend plausible corrective actions. It is therefore important that chemical process technicians remain confident and be able to interpret these rapidly evolving events to make sense of them; and make the correct decision among the choices available.

To this end, this paper proposes a pedagogical approach for training students in chemical process plant operation, using failure as a mean to stimulate learning, motivating them to learn the fundamentals of chemical engineering. Indeed, learning from accidents is already an important approach for the chemical industry, but the effect of digitalization makes such learning even more urgent. This paper suggests that the traditional approach of learning from accidents needs to be improved, and that such a pedagogy can be developed using the CDIO Framework. It is envision that other engineering disciplines can also adopt and/or adapt the underlying principles in the proposed pedagogy for their respective programs.

DIGITALIZATION AND COMPETENCY IN CHEMICAL PROCESS PLANT OPERATIONS

The Diploma in Chemical Engineering (DCHE) of Singapore Polytechnic is a 3-year program that produces graduates that work in a range of chemical processing industries. Graduates from DCHE typically found employment as Process Technicians, Technologists or Engineering Assistants. Many students also further their studies in the universities earning a degree in chemical engineering; and joining the industry as Chemical Engineers. Equipped with the basic knowledge from formal education, it took many more years to build up the expert knowledge to become a professional. In other words, human understanding is progressing at a far slower pace compared to the time it takes ML and AI to codify many years of experience – especially tacit ones – into a set of heuristics that guides the day-to-day operations of the chemical plants (e.g. predictive maintenance) and troubleshooting operational issues.

In a way, the problem depicted above is not very different from that challenged the aviation industry, where increased automation had increasingly taking over the functions of pilots in airlines. In his book *The Glass Cage*, Carr (2014) had argued that our increasing dependency on computers and technology is causing us to lose vital skills. While the automation of flying has made air travel safer, it has also resulted in the loss of cognitive control and lack of situational awareness among pilots. In some cases, such disconnect can have dramatic consequences: when an error occurs or the software fails to work as intended, manual control is abruptly thrust back into the hands of an overwhelmed pilot (Borowski, 2013). The recent aviation disaster that of the Boeing 737 MAX, reminds one of the question posed by Carr (2014): How will pilots react to a scenario that they were not trained for?

Like the aviation industry and the nuclear industry, the chemical processing industry also faced the challenge of managing risk where time-sensitive matters demanded timely human intervention that correctly address the developing emergency: Failure is not an option. This begs the question of whether engineers have the confidence in diagnosing an event he/she had never encountered before, and decide on the correct course of action to take, or for that matter, choose among several options as suggested by the company AI system. Already the chemical industry is grappling with the challenge of alarm management, where operating personnel are struggling to respond to the flood of alarms of all sorts (Noda, 2012; Jofriet, 2005).

Carr (2014) warned of the 2 threats confronting humans when using technology without thinking about them: *automation complacency* and *automation bias*. Automation complacency takes hold when a computer lulls us into a false sense of security. We became so confident that the machine will work flawlessly, handling any challenge that may arise, that we allow our attention to drift. Automation bias is closely related to automation complacency. It creeps in when people give undue weight to the information coming through their monitors. Their trust in the software becomes so strong that they ignore or discount other sources of information, including their own senses. It is the notion that because a result comes from a machine, it must be correct. We forget that the result may be flawed because it can only be as good as the algorithm under which it operates (Huth, 2016). The proliferation of advanced Industrial Internet of Things (IIoT) technologies such as smart sensors and transmitters are poised to exacerbate the situation with the big data they generated if not managed well.

This is in particular important to guard against a phenomenon known as the “watermelon effect” (Ellis, 2018) that arises from increasing use of dashboards to monitor chemical plant performance. The concern is the dangers of operating personnel not challenging apparent good performance, as indicated by the green outer layer of the watermelon, which represents indicators suggesting: “all is well”. However, deeper digging will reveal a red flesh inside indicating potential problem areas hidden from view, hence conveying a false sense of security. When problems do surfaced they represent dire situations that demanded quick resolutions, but human minds may be overwhelmed by the deluge of alarms.

LIMITATION OF TRAINING USING SIMULATION

Simulation-based learning had been widely studies, and recent report by Chernikova, et al (2020) reaffirmed its usefulness in promoting learning across higher education domain. In the chemical industry, simulation had been used successfully and effectively to train students in virtual plant operations in dealing with various problems in the plant. Simulations lend themselves readily to such trainings, as they are able to provide authentic scenarios that are not possible in the classroom, as the processes in the chemical industries are often carried out at high temperatures and pressure, for a wide range of chemicals many of which are toxic, flammable and/or explosive.

It is important to note that competency arising from such training needs to be supplemented with real-world work experience; which often takes many years to develop. For process technicians, this means performing various roles in the chemical plant, gain intimate working knowledge by utilizing their senses, notably sight, sound, smell, and touch. The use of IIoT technologies will drastically change the nature of work typically performed by process technicians in the plant. Use of smart sensors and controllers had not only taken over monitoring of the usual process variables of flow rates, temperatures, pressures, level, etc; but also those parameters usually carried out by process technicians during the routine walk-around the plants, such as functioning of steam traps, vibration of motors, etc.

Compared with the aviation industry, the chemical processing industries has many more plants that are different compared to aircraft types, handling large number of chemicals. Hence, it is impossible to train students in every conceivable chemical plant configurations, or chemical products. Even if one groups these plants into several categories based on the chemical products made, the number of different plants are still very large. As such, besides proprietary build simulators that are only available to company employees, much of the simulators available commercially focused on common chemical processes such as distillation, absorption, etc. Not only that, the cost of acquiring such training softwares even with academic discounts is still prohibitively large for widespread adoption in the universities.

For all the benefits accrued to simulation-based training, one must be mindful that the models were usually created based on known events, much like the aviation industry where the consequences had been experienced or studied; and procedures had been developed to deal with such an incident. As such, simulation-based training often emphasized executing a series of prescribed steps in operating manuals, i.e. the focus is aimed at preventing failures. Although a typical simulation package will include responding to process malfunction scenarios, still these are based on well-known operational problems such as loss of cooling water or pump trip. Indeed, Choudhari (2020) cautioned on the risk of inexperienced engineers relying on blind faith that simulations will deliver the right output.

It is common belief that simulators can provide sophisticated and accurate results in the shortest time, often unaware of the limitations and capabilities of a selected method or a selected equation. Likewise, Silverstein (2004) noted that there “appears to be a bias on the part of students towards trusting expensive simulator packages without considering how simulators work, what models are used, what assumptions are made, or potential sources of numerical error”. Today’s simulators are very sophisticated that to utilize its capability, adequate knowledge and specific process experience has become a prerequisite (Choudhari, 2020). Even so, the complexity of integrated chemical plants mean that it may not be possible to identify all possible interactions between the individual process units and hence to prepare students for all possible scenarios.

The training using process simulators for chemical plant operations often go along these steps:

- Students familiarize themselves with a given chemical process for which a simulation model is built. Such a process is typically a “generic” one, which in the case of distillation can be a simple 2-component separation of simple hydrocarbons or more complicated multi-component crude oil separation. A model for gas absorption typically involve the removal of hydrogen sulfide gas from a mixture of hydrocarbon gases. A simulation involving chemical reaction is typically one of a fixed-bed reactor for removal of sulfur compounds from a diesel product. These are the common models for processes typical in a refinery. Models are also available for the production of petrochemicals and fine chemicals. The bottom line here is that students must first learnt the process, equipment involved, operating conditions, feed materials that are used, and specifications of the desired product(s).
- Training usually starts with understanding how to operate the plant, by starting the simulation in “steady-state” mode, a condition whereby the process is running smoothly. Students start to make small changes to the plant, for example; changes in composition of the feed materials in a distillation unit, raising the flowrate of a solvent to a gas absorption unit, or increasing the operating temperature of a chemical reactor. Students observe how the entire process respond to these deliberate changes by monitoring various trend graphs generated by the simulator.
- The next phase of training then go into learning about malfunctions, and how to respond to them. This usually made use of several scenarios already available (pre-programmed) from the simulation package, and students go through a step-by-step process of rectifying the situation to bring the process back to its steady-state condition. Under a malfunction scenario situation, students must interpret the cause of alarms that were triggered, which can indicate deviations from desired operating conditions or potential issues with certain equipment; and they need to make sense of the myriad of data to pin-point the root cause and then take corrective actions. Students get to connect the observed data with a given type of malfunction.
- The last phase often involved an unknown issue being triggered, and students need to troubleshoot the situation to arrive at an acceptable way to address the issue. Often this is based on any one of the malfunctions that students had practiced before in the earlier phase. This phase may sound rather straight forward, as it appears that students already “make the connections” between a given malfunction and the observed plant performance. In practice, it is more challenging, as different malfunctions often give rise to the same alarms being triggered, as the process variables are all interconnected and can affect one another. The challenge becomes one of identifying the initial triggering event and reason through the malfunction process to ascertain the best corrective measure to take.

LEARNING FROM FAILURE: LITERATURE REVIEW

The chemical industries had consciously documented all major and minor accidents as well as near misses with the aim of making all processes safer. In order to prevent accidents it is essential to learn from previous accidents and incidents. Learning from accidents is to extract, put together and analyse and also to communicate and bring back knowledge on accidents and near-accidents, from discovery to course of event, damage, and cause to all who need this information. The purpose is to prevent the occurrence of similar events, to limit damage, and thereby improve safety work (Lindberg, et al, 2010). Learning from accidents are normally introduced through case studies (see for example, Weibull, et al, 2020; Kletz, 2001; Jefferson, et al, 1997). However, despite the numerous books and other publications on the topic, many organisations still faced challenges in reducing the number of safety incidents.

This can be attributed partly to the failure to learn from accidents (Drupsteen, et al, 2013). Barriers to learning from incidents and accidents are already widely documented elsewhere and will not be discussed here (see for example ESReDA, 2015; RoSPA, 2015). Suffice to note here that it is especially difficult for one to learn from failures of a technical nature, as one lacks the basic scientific know-how to be able to draw inferences from the experiences systematically, as well as the presence of complex systems that are inherently difficult to understand (Cannon & Edmondson, 2005). This may also be a reason why learning using simulations are not usually introduced until later years of study. Indeed, drawing on historical data, Mannan & Waldram (2014) noted that the international community of process engineers has not been good at learning lessons from their past accidents, and called for a paradigm shift in learning from failure.

This last point is also a poignant reminder of how students are trained: they are often given the information needed to “solve problems” during tutorials. Usually this involved them putting in the right numbers into the right equations (often already given), so that they can arrived at a certain pre-determined “answer”. Students do not question the reasonableness of their solutions. In doing so, we had inadvertently, “design-out” failures from the learning process.

This paper attempts to look at failures from a different perspective: that of learning from failure from the business world, entrepreneurship or the design-related education. More specifically, we look into ways to at “failure on purpose”, or what Sitkin (1996) termed “intelligent failure”. The latter arise from Sitkin’s observation that most organizations tend to try to engineer failures out of their processes, thus robbing themselves of the opportunity to identify weaknesses before small failures become big catastrophes. In fact, extant models were often designed for efficient and structured approaches that emphasize failure avoidance (Tawfik, et al, 2015). Another term often used is “failure-based learning” (Tawfik, et al, 2015). These terms are used interchangeably in this paper.

Learning from failure is often celebrated in the design world, to quote a famous saying by John C. Maxwell: "Fail early, fail often, but always fail forward”. Jackson, et al (2022) noted that failure is part-and-parcel of the design process: it is embedded in the design process. Iteration is an important attribute of design, and failure would seem to be an accepted, even expected, part of design and a learning opportunity. The benefits include: (a) Failure as a mechanism to uncover key concepts from students; and (b) Failure induces thoughtfulness in problem solving. To realize these benefits, students need to be aware of their failures. In other words, for failures to be a useful learning experience, students need to analyze failures, understand what happened, why it happened, and how to move forward.

This is especially important to students, who due to their lack of experience and hence lack of confidence, tend to be obsessed with “concreteness”, for the “how to do”, putting heavy emphasis on following procedures; thus limiting their interest exclusively to “the solutions”. The proposed approach will refocus the attention to the strategic value of analysis and praxis; to connect to theories and make-sense of the data (Dominici, 2020).
A question may be posed whether learning from failure is a form of problem-based learning (PBL). To the best of the author’s knowledge, the extant literature did not explored such relationship. To be sure, works on problem-based learning certainly highlighted the role of failure in promoting student learning, but more emphasis is placed on role of teacher in facilitating the learning process. An interesting work is one reported by Dobson, et al (2021) who mentioned the use of problem-based learning on the teaching of entrepreneurship and how learning from failures in business plans and models; but the focus in not on the connections between designing learning tasks that deliberately resulted in failure. There are obviously various discussions on PBL, and it is not the intent of this paper to discuss at length the method of engaging students in learning. Readers interested in the development of PBL, how it works and the challenges is posed can refer to the works of Servant-Miklos (2020). The remainder of this section briefly explains what problem-based learning is, and how does it compared with learning from failure.

Suffice for the purpose of this paper is the reference to the works of Hmelo-Silver (2004) who explains problem-based learning (PBL) as an instructional method in which students learn through facilitated problem solving. In PBL, student learning centres on a complex problem that does not have a single correct answer. Students work in collaborative groups to identify what they need to learn in order to solve a problem. They engage in self-directed learning (SDL) and then apply their new knowledge to the problem and reflect on what they learned and the effectiveness of the strategies employed. The teacher acts to facilitate the learning process rather than to provide knowledge. The goals of PBL include helping students develop: (1) flexible knowledge, (2) effective problem-solving skills, (3) SDL skills, (4) effective collaboration skills, and (5) intrinsic motivation.

Tawfik, et al (2015) on the hand, argue that existing “learning design often focus on templates of successful problem-solving to support students”. They noted “theories from numerous domains suggest that failure is a fundamental aspect of the learning process” and that educators should make use of learning from failure to promote student learning. Educators should create “opportunities for learners to encounter and overcome failures during problem-solving as a way to refine extant mental models and promote conceptual change”. Hence, from a problem-solving perspective, learning from failure can be viewed as a form of PBL. It too, aims at developing students’ problem-solving skills. However, it is different from PBL in that – at least as far as chemical plant operation is concerned – there is often one correct solution to bring the chemical process from disturbance back to steady operation. Learning from failure in chemical plant operations requires that students search their prior knowledge to see connections between various process variables shown on dashboards with issues with the specific process operation on hand. SDL skills may not play a key role here, as the key step in tackling chemical process operational problems is to connect-the-dots among the many indicators (usually manifest themselves in the form of alarms). Hence the process technicians will first “dig deep” into his/her knowledge base to formulate plausible cause-and-effect relationships among the indicators, and where needed, able to identify what other data are needed to confirm or disprove a hypothesis.

Other than problem-solving skills, the goals of learning from failure in the context of chemical process operation from the perspective of this work is to help students develop: (1) sense-making skills, notably discerning the relationships between process variables, (2) ability to work under pressure, (3) resilience, (4) self-reflection, and (5) self-confidence in decision-making. These are the traits or dispositions that the author called “failure-tolerant” mindset. The next section explores in greater details how to develop the skills in seeing connections in chemical process operations.

LEARNING FROM FAILURE IN CHEMICAL PROCESS OPERATIONS: BACK TO BASICS

To this end, we need to review how we teach problem solving in chemical engineering. Failure in chemical processing industries can take several forms, starting with failure in design, which will create other operational problems later when the faulty design was adopted and implemented. An example of failure at the design stage is that an equipment was wrongly sized, or wrong materials of construction specified. The former may be due to the use of wrong equations or correlations, or using inappropriate properties of the mixtures being handled in the ensuing calculations. Failure at the operation stage may result directly from the fault at the design stage, but failure can also occur due to the plant not being operated correctly, for example, not following standard operating procedures. The type of failure of concern here is one that arise from abnormal operating conditions, for instance: (a) due to changes in properties of the mixture being handled; or presence of impurities in feed; (b) process upsets such as loss of heating or cooling; or damage to equipment (e.g. due to wear and tear).

Due to the large varieties in chemical plant operations, it is not possible nor desirable to teach students all the different chemical processes. It is also not practical to have simulation models that cover all aspects of chemical processing. What we can and should do, it to go back to basics: emphasising more on the chemical engineering principles and fundamentals. Two areas that we specifically wanted to focus on are:

(1) Relationship between process variables
(2) Visualization of chemical processes operations

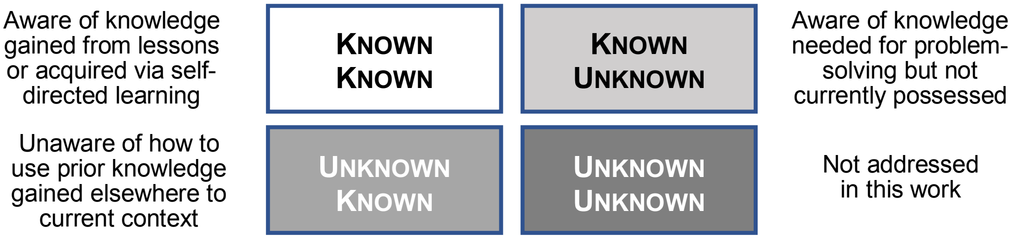
A process variable in our context refer to a parameter in chemical processing plant that can changed and is often monitored so as to maintain it at a constant value. Examples of process variables include flow rate, temperature, pressure, composition. Chemical engineering as a discipline is unique in the sense that it deals with mixtures most of the time. Mixtures are substances that contain more than one components, and in the case of crude oil, there can be hundreds of components. Mixture properties are affected by the relative compositions of substances in the mix, and their interactions with one another. Often the chemical processes take place under high pressure and temperature, in enclosed containers made of carbon steel or stainless steel. Hence, the contents are not visible. Changes in plant operating temperatures and pressures can affect the mixture compositions and their distribution between the phases (typically between gaseous and liquid phases) which in turn also affect mixture properties, and hence product specifications.

Learning from Failure: Understand the Relationship between Process Variables

Being able to identify the relationships between various variables is useful in helping to make sense of the myriad of information that came through the many sensors in a typical chemical plant and displayed on performance dashboards. Being able to visualize the chemical processes enable one to explore via the mind’s eyes, potential hazards of a proposed course of action, especially when responding to an emergency in a chemical plant.

This aspect of learning is often neglected. The author opined that this is often the result from the current dominant approach to teaching, where different engineering fundamentals (e.g. fluid flow, heat transfer, process safety, etc) are often taught in separate modules, resulting in compartmentalized learning. In addition, the tendency of faculty to focus on such problem solving within one's own module often means that the focus is on applying the correct equations; whereas the needs to ensure that the correct data are used is often neglected.

Developing students' ability to see connections between various process variables also helped them to integrate knowledge acquired in different chemical engineering core modules, taught separately. We found that our students often do not know how to make use of what they had learnt in one module and connect them to another module. We termed this the challenge of "Unknown Known" as shown in Figure 1, in the lower left quadrant. This figure is our interpretation of the Rumsfeld Matrix, named after Donald Rumsfeld the late former U.S. Secretary of Defence, who stated in his February 2002 Defence Department briefing: "*There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know*." (Logan, 2009).



Aware of knowledge gained from lessons or acquired via self-directed learning	**KNOWN KNOWN**	**KNOWN UNKNOWN**	Aware of knowledge needed for problem-solving but not currently possessed
Unaware of how to use prior knowledge gained elsewhere to current context	**UNKNOWN KNOWN**	**UNKNOWN UNKNOWN**	Not addressed in this work

Figure 1. Rumsfeld's Matrix adapted to Student Learning

Focusing on helping students making connections between the modules they learnt is therefore the focus on our approach to teaching the "fundamentals of fundamentals". More specifically the emphasis is to get students to be aware of their "unknown knowns". This will start with understanding the relationship between process variables, by recognizing how a change in the process operating condition(s) will affect other process variables. This can be covered in Year 1 in modules such as *Laboratory & Process Skills 1* (in Semester 1) and *Laboratory & Process Skills 2* (in Semester 2). Then in Year 2, more connections can be made between the "unknown knowns" in terms of basic equipment covered in Year 1 Semester 2 (in modules such as *Heat Transfer & Equipment*), and more sophisticated ones in Year 2 Semester 1 (such as distillation in *Separation Processes*; chemical reactors in *Chemical Reaction Engineering*). Deeper relationships between process variables and these equipment can be further explored in modules such as *Process Operation Skills 1* (in Year 2 Semester 1) and *Process Operation Skills 2* (in Year 2 Semester 2).

Suitable integrated learning experiences can be designed for these modules to change students' mindset about failure in a progressive manner; by deliberately "build in" various aspects of failure in chemical plant operations. This is shown in Figure 2 where students will first understanding the consequences resulting from failure. Then, they will learn to identify signs of potential problem areas by overcoming their blind spots in the "unknown knowns"; conduct inquiries into causes and sources of failures; and gradually learn to embrace failure as a source of learning. They will gradually develop the requisite confidence to achieve a sense of mastery in dealing with problems in chemical plant operations.

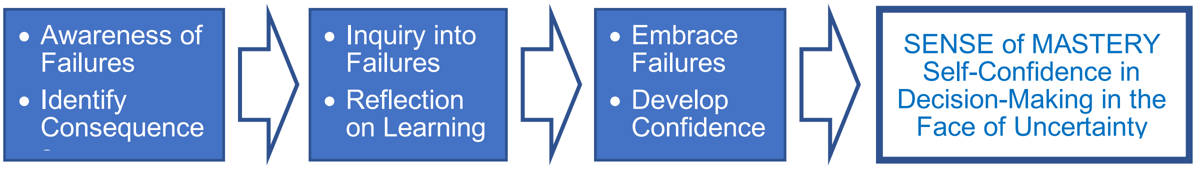


Figure 2. Pedagogy for Learning from Failure

The next section explores in details how we can use the CDIO Framework to guide us in the design of learning tasks using failure-based learning.

CDIO FRAMEWORK TO SUPPORT LEARNING FROM FAILURE

The CDIO Framework lends itself naturally to provide guidance to develop students' capacity to learn from failure. Essentially, we make use of the following 3 guidance questions:

1. Need: What is the professional role and practical context of the profession?
2. Learning outcomes: What knowledge, skills and attitudes should students (and adult learners) possess as they graduate from our programs, and at what level of proficiency?
3. Curriculum, workspace, teaching, learning and assessment: How can we do better at ensuring that students and adult learners learn these skills?

The CDIO Syllabus provide key learning outcomes of the skills and attitudes needed to support learning from failure, for example:

2.3.4	Trade-offs, Synergies, Judgment and Balance in Resolution
2.4.1	Demonstrate Positive Attitude and Willingness to Make Decisions in Face of Uncertainty
2.4.2	Perseverance, Urgency and Will to Deliver
2.4.6	Self-Awareness, Self-Reflection, Metacognition and Knowledge Integration
4.1.2	Address the Impact of Engineering on Society and the Environment

These skills and attitudes can build on abilities already covered in existing modules, such as of growth mindset, intrinsic motivation, teamwork and communications, critical thinking and problem-solving. The extant literature also provide guidance on strategies that can be used to include learning from failure in students' experience. A good reference is provided by Tewfik, et al (2015) as shown in Table 1; which supports the pedagogy detailed in Figure 2.

Table 1. Instructional Design Principles for Failure-based Learning (Tawfik, et al, 2015)

Guidelines	Examples of Strategies
1. Allow learners to identify failure	
Define conditions for failure	Learners should be prompted to address the conditions for success and failure before problem-solving. Otherwise, they may not be primed to investigate failure-states
Identify failure perspectives	Learners should be given the opportunity to redefine the success and failure from an alternative perspective after the initial parameters for failure are constructed to promote cognitive flexibility
2. Design learning environments to intentionally encounter failure	
Failure-based question prompts	Question prompts designed for students to discuss and/or encounter failures students might otherwise overlook

	Generate failure-based causal models	Learners could be asked to explicitly generate a causal model that may result in a failed solution from a specific perspective or lens
	Models of failure	Case libraries could be provided as a series of failure-based narratives that learners could access as just-in-time resources
3.	Support inquiry into failure for analogical transfer	
	Inquiry and hypothesis generation	Prompts the learner to reflect on their experience and misconceptions Learners can be asked to generate and justify reasons for the fault-states and breakdowns in causal reasoning
	Reflection on failure	Question prompts embedded to encourage learners to reflect on individual introspection; artefacts of the failure context; and systemic perspective of the failure
	Identify opportunities for transfer	Space to manipulation variables or parameters so that learners are able to demarcate the appropriate conditions for transfer
4.	Support solution generation to resolve failures	
		Space or prompts provided within a learning environment to help students generate, debate, select, apply, and evaluate solutions to resolve root causes to breakdowns of the micro-failures

The strategies presented in Table 1 can easily fit into the generic descriptors of appropriate CDIO core standards. They serve to illustrate specific examples of how the CDIO Standards can be interpreted when applied to promote learning failures. This is shown in Table 2.

Table 2. Selected CDIO Core Standards to Guide Designing for Learning from Failure

No.	Standard Name	Guidance to Designing for Learning from Failure
1	The Context	Describe possible workplace scenarios, focusing on work items that opportunities to introduce elements of failure that promotes learning, either from mistakes made, or in anticipating probable failures; and come up with plausible solution(s).
2	Learning Outcomes	Key skills and attitudes need to develop capacity to learn from failure, as per CDIO Syllabus; which also serve as expectations that will be clearly communicated to students.
3	Integrated Curriculum	Provide guidance on how to sequence, in suitable modules, lessons that promote learning from failure in a progressive manner, from initial exposure to failure, perspective on failures, and its eventual acceptance in a positive light; i.e. towards the gradual shift in mindset towards embracing failure. Such sequence will build on prior knowledge, skills and attitudes already integrated.
7	Integrated Learning Experiences	Simulated real-world work environments will need to be designed to provide students with various opportunities to experience failure in assigned tasks and repeated practice. Opportunities to transfer from one context to another will be enthusiastically explored.
8	Active Learning	Flipped learning will be leveraged upon to engage students in the in-class components to stimulate critical thinking, such as discussing about the causal model(s) of failures.
9	Enhance of Faculty Competence	Faculty need to be trained as facilitators, with strong interpersonal skills to encourage open-mindedness in students, to support learning from failures alongside the technical module one is teaching.
10	Enhance of Faculty Teaching Competence	Faculty need to be familiar with pedagogy presented in this paper, and trained to design integrated learning experiences with experiential learning to scaffold students' development of positive outlook towards learning from failure.

11	Learning Assessment	Approaches to evaluate reliably the progressive development of failure-tolerant mindset will need to be formulated; and sufficient time devoted to giving students feedback to improve learning. Reflection on failure will be a key component to support development of failure-tolerant mindset.
12	Program Evaluation	Review the integration effort to identify areas of improvement as part of the module review process in SP Academic Quality Management System.

Table 3 provides some examples of how learning tasks will progressively develop various aspects of competency needed to learn from failure over the 4 semesters of study, to better prepare them to handle operations of chemical plants when they join the workforce as process technicians upon graduation. Specific teaching and learning practices will be developed for each stage of study using the guidance from Table 2. It is expected that by Year 3, students are comfortable at encountering failures in process plant operations, fully understand the consequences of failures, will strive to operate chemical plants safely to avoid any catastrophic failures.

Table 3. Learning Tasks to Promote Progressive Development in Learning from Failure

Year 1 Semester 1	Year 1 Semester 2	Year 2 Semester 1	Year 2 Semester 2
Overall approach: Leverage on current effort in instilling growth mindset in students, to get them familiar with handling big data; promote understanding of relationship between process variables via appropriate data visualizations; to support various stage of development for learning from failure.			
Develop competency in Data Fluency: from handling of big data to their visualization to aid identifying relationship between process variables			
Refine current learning task to include selecting and interpreting large data set from literature (often in tabular format to discern possible relationships between various properties of a mixture.	Create basic-level data visualization to display appropriate process variables to identify potential issue in a small-scale pilot plant. Explain potential consequences if safety is compromised.	Create more complex data visualization using more process variables based on moderately complex pilot plants, but still limited to operations within the same single piece of equipment.	Create complex data visualization using more process variables based on complex pilot plants. This can now be across several plant items in the same process unit, or even across process units.
Develop competency in preparing and/or using Experimental/Operating Procedures: visualization of steps involved and consequences of not adhering to procedures			
Develop procedures for some experiments, based on resources provided. Visualize ways in which an experiment is to be conducted based on the procedures prepared, and identify potential safety hazards.	Identify mistakes in a given set of standard operating procedures that was deliberately arranged in wrong order that may result in undesired or negative consequences (via visualization); and to correct these mistakes.	Operate moderately complex pilot plants; explain rationale for prescribed sequence in operating procedures; identify potential process safety hazards and consequences if deviate from operating procedures.	Use dynamic simulation and/or digital twin to investigate different outcomes if deviate from prescribed set of operating procedures for complex pilot plants (available as digital models only; not physical items).
Develop competency in explaining relationships between process variables during chemical plant operations; and potential consequences			

Conduct experiments, observe and identify possible sources of errors; explicitly record all observations; visualize possible conditions that can lead to failure; and identify areas of improvement.	Operate simple pilot plants, identify potential hazard during plant operation; leverage on vendor mistakes in the plants (left uncorrected to provide learning opportunities, so long as safety is not being compromised).	Operate moderately complex pilot plants; identify potential hazards; identify potential impact of mal-function in one plant item on other plant items within the same process unit, and explain the reasons.	Operate relatively complex virtual pilot plants (digital twin and/ or dynamic simulation), explain using observed process variables the causes of various simulated scenarios where failure in encountered.
For tracking of students' development of change in attitude towards failure, we will use focus group discussions, along with surveys administered alongside existing initiative on teamwork development. Reflection journals will be used: at different stages of study, students are to document their learnings and changes in perceptions regarding failures and coping with the changes.			

There are other aspects of chemical engineering education where benefits of learning from failure can be realized. One ideas presented earlier represent one main pathway of competency development: that of process plant operation to prepare students to work in the chemical processing industries. The DCHE curriculum had another pathway of chemical product design that equip students with the competency of using chemical engineering sciences and principles to design, conceive, implement and operate chemical products, systems or services. This is another area rich in opportunities to introduce deliberate failure into students' learning, especially via the "project spine" in the DCHE curriculum (Cheah, 2021). This area is part of a wider research topic the author is involved in a project with the Singapore University of Technology and Design (SUTD) and will be the topic of a separate discussion not covered in this paper.

MOVING AHEAD: DEVELOP A "LEARNING FROM FAILURE" MINDSET

The Industry 4.0 revolution will cause significant effects, such as the new occupations and job profiles, changes to employment forms and a more important role for the platform economy, generating challenges for social policy. The development of human capital and consumer behaviour will be impacted. The educational profile of the human capital is necessarily changing and new approaches to education systems must be introduced (Gajek, et al, 2022).

This paper had discussed how learning from failure can be implemented in a chemical engineering curriculum, specifically focusing on chemical process operations. The approach suggested in the paper is to first focus on connecting the dots among the many process variables in a typical chemical plant, so that they can discern how these process variables are related and interacted with one another. This, coupled with domain knowledge of how the chemical processing plant works, will better equip students to perform as process technicians in the chemical plants; that they are able to make-sense of the plethora of data that come through the plant dashboard, analyse any output from the plant AI system; in particular during process upset.

We hope to prepare a new breed of graduates who have the technical competency and mental capacity to visualize potential failures, to benefit from ability to anticipate such failures, and take corrective measures to prevent them from happening. In this way, we hope that our graduates will have the self-confidence to make decisions in face of uncertainly in a digitalized chemical industry enabled with various AI tools that support plant operations.

Much remains to be done, to develop the learning tasks as suggested in Table 3. Fellow colleagues will need be engaged to buy into this new approach of training – will be a challenging feat in view of today's workload for academic staff! They have to make to existing learning tasks or design new ones. We also need to monitor students' learning progress from Year 1 to Year 3, for example via a longitudinal study involving questionnaire surveys, focus group discussions, interviews, etc.

To this end, we also need to better prepare our lecturers to engage students differently, especially in allaying students' fear of failure in the 'academic sense', i.e. resulting in poor grades. We will be exploring various professional development workshops, for example with SUTD. A working group on learning from failure had been proposed and accepted for this International CDIO Conference, and we welcome like-minded CDIO collaborators to work with us on this aspect.

CONCLUSION

This paper shares an approach based on the CDIO Framework that enabled learnings from failures in the chemical engineering curriculum, focusing specifically on chemical plant operations. The aim is to better prepare graduates to meet the workplace demand equipped with sound technical knowledge to make informed decisions in face of challenges, particularly those of time-sensitive manner. A complete pedagogical approach had been presented taking into considerations extant literature about learning from failure; and an alternative way of training students grounded in the principles from the CDIO Framework is offered.

FINANCIAL SUPPORT ACKNOWLEDGEMENTS

The author(s) received no financial support for this work.

REFERENCES

Borowski, A. (2013). *Book Review: The Glass Cage: Where Automation is Taking Us by Nicholas Carr*, LSE Review of Books, London School of Economics and Political Science

Cannon, M.D. & Edmondson, A.C. (2005). Failing to Learn and Learning to Fail (Intelligently): How Great Organizations Put Failure to Work to Innovate and Improve, *Long Range Planning*, Vol.38, pp.299-319

Carr, N. (2014). *The Glass Cage: Automation and Us*, W.M. Norton & Company, New York, London

Cheah, S.M. (2021). Sustainable Development in Chemical Engineering Curriculum: Review and Moving Ahead, *Proceedings of the 17th International CDIO Conference*, hosted on-line by Chulalongkorn University & Rajamangala University of Technology Thanyaburi, June 21-23; Bangkok, Thailand

Chernikova, O., Heitzmann, N., Stadley, M., Holzberger, D., Seidel, T. & Fischer, F. (2020). Simulation-based Learning in Higher Education: A Meta-Analysis, *Review of Educational Research*, Vol.90, No.4, pp.499-541

Choudhari, A. (2020). Should You Rely on Your Simulation Results? *PTQ Magazine*, Q4, pp.47-51

Dobson, J.A., Nieto, Y.C., Dobson, L. & Ochoa, A.M. (2021). Success through Failure: Towards a Problem-based Approach to Entrepreneurship, *Entrepreneurship Education and Pedagogy*, Vol.4, Issue 3, pp.225-260

Dominici, P. (2019). Educating for the Future in the Age of Obsolescence, *IEEE 18th International Conference on Cognitive Informatics & Cognitive Computing (ICCI*CC)*, July 23-25; Milan, Italy

Drupsteen, L., Groeneweg, J. & Zwetsloot, G.I.J.M. (2013). Critical Steps in Learning From Incidents: Using Learning Potential in the Process From Reporting an Incident to Accident Prevention, *International Journal of Occupational Safety and Ergonomics*, 19:1, pp.63-77

Edmondson, A.C. (2011). Strategies for Learning from Failure, *Harvard Business Review*, April Issue

Ellis, G. (2018). The "Watermelon Effect" – Does a Green Dashboard mean a Healthy Facility?", *Loss Prevention Bulletin*, No.264, Institution of Chemical Engineers

ESReDA (2015). *Barriers to Learning from Incidents and Accidents*, European Safety, Reliability & Data Association

Gajek, A., Fabiano, B., Laurent, A. & Jensen, N. (2022). Process Safety Education of Future Employee 4.0 in Industry 4.0, *Journal of Loss Prevention in the Process Industries*, Vol.75, pp.1-29

Hmelo-Silver, C.E. (2004). Problem-Based Learning: What and How Do Students Learn? *Educational Psychology Review,* Vol.16, pp.235-266

Huth, J. (2016). Book Review: The Glass Cage: Where Automation is Taking Us by Nicholas Carr, *American Journal of Physics*, Vol.84, No.7, pp.565

Kletz, T. (2001). *Learning from Accidents*, 3rd. Ed, Tailor & Francis

Jackson, A., Godwin, A., Bartholomew, S. & Mentzer, N. (2022). Learning from Failure: A Systematized Review, *International Journal of Technology and Design Education*, Vol.32, pp.1853-1873

Jefferson, M., Chung, P.W.H. & Kletz, T.A. (1997). Learning the Lessons from Past Accidents, *Hazards XXIII, IChemE Symposium Series No.141*, pp.217-226

Jofriet, P. (2005). Alarm Management: Process and System Alarms are Intended to Assure Efficient Process-Plant Operations and Even, Occasionally, Save Lives. But in Too Many Plants, the Alarm System has Paradoxically Evolved into a Nuisance. A Five-step Procedure can Put a Degenerate Alarm System Aright, *Chemical Engineering*, Vol.112, No.2

Lindberg, A-K., Hansson, S.O. & Rollenhagen, C. (2010). Learning from Accidents – What More Do We Need to Know? *Safety Science*, Vol. 48, Issue 6, pp.714-721

Logan, D.C. (2009). Known Knowns, Known Unknowns, Unknown Unknowns and the Propagation of Scientific Enquiry, *Journal of Experimental Botany*, Vol.60, No.3, pp.712-714

Mannan, M.S. & Waldram, S.P. (2014). Learning Lessons from Incidents: A Paradigm Shift is Overdue, *Process Safety and Environmental Protection*, Vol.92, Issue 6, pp.760-765

Noda, M.(2012). Research Challenges in Alarm Management for Safe and Stable Plant Operations in Chemical Process Industries, *Computer Aided Chemical Engineering*, Vol.31, pp.107-114

RoSPA (2015). *Learning to Learn from Accidents*, Royal Society for the Prevention of Accidents

Servant-Miklos, V. (2020). Problem-oriented Project Work and Problem-based Learning: "Mind the Gap!", *Interdisciplinary Journal of Problem-based Learning*, Vol.14, Issue 1, pp.107-122

Silverstein, D.L. (2004). Process Simulation Failure as a Learning Tool, *Proceedings of the 111th ASEE Annual Conference & Exposition*, June 20-23; Salt Lake City, Utah

Sitkin, S.B. (1996). Learning Through Failure: The Strategy of Small Losses, in *Organizational Learning*, Cohen, M.D. & Sproull, L.S. (eds), Thousand Oaks, CA Sage

Tawfik, A.A., Rong, H. & Choi, I. (2015). Failing to Learn: Towards a Unified Design Approach for Failure-based Learning, *Educational Technology Research & Development*, Vol.63, pp.975-994

Weibull, B., Fredstrom, C. & Wood, M.H. (2020). *Lessons Learned from Accidents: Key Points and Conclusions for Seveso Inspectors of Major Chemical Hazard Sites*, EUR 30391 EN, Luxembourg, Publications Office of the European Union

Zandi, M., Glassey, J. & Young, B. (2022). Mind the Gap, *The Chemical Engineer*, October, pp.41-43

BIOGRAPHICAL INFORMATION

Sin-Moh Cheah is the Centre Director of the SP-CDIO Centre for Innovative Teaching and Learning; under the Department of Educational Development, Singapore Polytechnic. He is also the Lead Teaching and Learning Specialist in the School of Chemical and Life Sciences, Singapore Polytechnic. He has more than 15 years of experience implementing CDIO in the Diploma in Chemical Engineering curriculum, and had conducted various CDIO workshops for universities in Asia, for various disciplinary programs. His academic interests include curriculum revamp, academic coaching and mentoring, and using ICT in education.

Corresponding author:
Mr. Sin-Moh Cheah
School of Chemical & Life Sciences,
Singapore Polytechnic
500 Dover Road, Singapore 139651
smcheah@sp.edu.sg