# EMBRACING FAILURE IN ENGINEERING EDUCATION: A COMPARATIVE STUDY OF DESIGN THINKING APPROACHES

**Thijs Willems, Qian Huang, Ameek Kaur, King Wang Poon**

Singapore University of Technology and Design, Lee Kuan Yew Centre for Innovative Cities

## ABSTRACT

In many engineering sectors, cycles of prototyping have shortened because of new technological advancements and more pressing urgencies to be innovative. As a consequence, important skills and attitudes that were traditionally learned on the job have now become a responsibility of institutes of higher education. Universities are not only expected to develop students to be industry-ready when they graduate, but they must assure they are innovation-ready as well. One way of doing so is to make students innovate on a more regular basis and by making them more comfortable with learning from the failures arising out of such shortened cycles of innovation. Learning from failure is well studied and established in some areas of education, such as the ‘Productive Failure’ approach in the domain of mathematics. However, lessons learned from such contexts may not immediately apply to the engineering context. By comparing a one semester Design Thinking and Innovation Course with a one-week cross-cultural design thinking workshop at an engineering university in Singapore, this study aims to find out how learning from failure is manifested to engineering students. The study, in drawing on observations, interview data, and students’ reflections provides several insights, such as identifying different types of failures that students encounter in their design work and highlighting two core issues (teamwork and grades) that may facilitate or hamper the extent to which students are willing to innovate. This paper gives pedagogical suggestions on how design and innovation can be taught to engineering students, specifically by taking the perspective of learning from failure and its relationship with innovation into account. This paper thus addresses the CDIO Standards 5 and 7.

## KEYWORDS

Learning from failure, innovation, creativity, design, Standards 5, 7

## INTRODUCTION

In the dynamic context of contemporary engineering education, institutions are tasked with a critical mission: to cultivate graduates who are not only adept at navigating industry demands but who are also at the forefront of innovation. This mission has gained urgency in light of the rapid prototyping cycles propelled by technological advancements, pressing educators to transcend traditional teaching paradigms. The emphasis has shifted towards fostering skills and attitudes that enable students to manage and learn from failures—a process that has become increasingly crucial given the innovative imperatives of modern engineering practice (Amabile, 1988; GII, 2018).

One way to stimulate such learning is by putting greater emphasis on the role of failure in education. In rapid prototyping, students are expected to go through many cycles of iteration and in order for these to lead to innovative and new solutions the idea of trial and error is key. But fear of failure may stifle innovation, and the classroom can be a safe space in which students can experiment and develop curiosity to explore different or creative solutions (Foley, Foley, & Kyas, 2022). Fortunately, the education literature has looked into this topic with great interests, noteworthy via the work on ‘Productive Failure’ as developed by Manu Kapur (2008, 2014). However, the concept of learning from failure, established in domains such as mathematics through the 'Productive Failure' approach (Kapur, 2008), encounters unique complexities within the engineering landscape. Unlike the deterministic nature of mathematical problems, engineering challenges present a spectrum of viable solutions, each accompanied by its own set of uncertainties (Clifford, 1988; Dym et al., 2013).

This divergence calls for an approach to learning from failure that is specifically attuned to the multifaceted nature of engineering design and innovation (Jackson et al., 2021). Prior work illustrated the difference of educational value of failure in different engineering contexts. Cheah (2023), for instance, looked at developing a pedagogy around failure as a learning opportunity in safety critical environments. In chemical engineering education, learning from process plant operation failures can enhance students' understanding of complex systems and fosters resilience. Huang et al. (2023), on the other hand, discussed this in the context of a robotics competition. Their study shows how different types of failures promote creativity and problem-solving in tackling engineering challenges. These examples highlight failure as a pivotal learning tool in developing innovative and resilient engineering professionals.

The study behind the current paper conducts a comparative analysis of two design thinking courses—a semester-long course and a one-week cross-cultural program—at an engineering university in Singapore. This comparison is not merely an academic exercise, but an exploration aimed at unpacking the diverse manifestations of learning from failure in engineering education (Hong & Choi, 2011). The comparative framework allows for an examination of how varying factors such as durations and contexts influence the learning outcomes associated with failure (Kapur & Bielaczyc, 2012).

Engineering students, based on our findings, grapple with a range of failures—incidental, iterative, and intentional. These failures, though integral to the iterative design process, often remain implicit, challenging educators to make the lessons they embody more explicit and actionable for students. This task is critical for the cultivation of innovative thinking and aligns with Amabile et al.'s (2018) perspectives on the social psychology of creativity, emphasizing the importance of context (e.g. the way a classroom is managed or a class is conducted) in nurturing creative problem-solving skills.

Moreover, the study's insights into the dynamics of teamwork underscore the complex interplay between collaboration and innovation for engineering students. Team-based challenges can serve as fertile ground for innovation yet also pose significant obstacles that must be skilfully navigated (Kim, 2005). The role of grades further complicates this landscape, with our findings suggesting that the traditional emphasis on grades may inhibit risk-taking and stifle the innovative spirit required for tackling complex engineering problems (Daly, Mosyjowski & Seifert, 2014; Zhou, 2012).

In the broader context of the CDIO (Conceive-Design-Implement-Operate) initiative, this paper contributes to the discourse on pedagogical strategies that enhance design-implement experiences (Standard 5) and integrated learning experiences (Standard 7). The research provides a nuanced insight in the pedagogical implications of learning from failure, suggesting that embracing such an approach could significantly enrich the educational experiences of engineering students (Stretch & Roehrig, 2021; Marks & Chase, 2019).

Our insights are supported by a substantial body of literature that underlines the transformative potential of embracing failure within educational frameworks. For instance, the work of DiNapoli (2018) and Pan, Kuo, and Strobel (2010) suggest that perseverance in the face of challenging tasks is critical for deep learning, while Tawfik, Rong, and Choi (2015) propose a unified design approach for failure-based learning. These scholarly contributions highlight the need for educational strategies that not only encourage students to confront and learn from failure but also to harness these experiences to fuel creativity and innovation (Amabile et al., 2018; Stretch & Roehrig, 2021).

Furthermore, cultural considerations play a significant role in how students perceive and respond to failure. The work of Cheng and Hong (2017) and Kim (2005) sheds light on cultural dimensions of creativity and learning, indicating that an understanding of these cultural nuances is imperative for designing effective learning interventions in diverse educational settings. These insights are particularly relevant for the cross-cultural component of the study, emphasizing the importance of culturally sensitive pedagogy in engineering education (Hubner et al., 2022). The academic dialogue surrounding failure in education is enriched by the works of Telenko et al. (2015) who explore the boundaries of design thinking in engineering education. Their research underscores the importance of experiential learning and the need for educational models that prepare students for the realities of the engineering profession, where failure is not only a possibility but an opportunity for growth and innovation (Lee, 2020; Foley, Foley, & Kyas, 2022).

In conclusion, this paper aims to understand the role of failure in engineering education. It lays the groundwork for the study's methodology and findings, offering pedagogical insights that are aligned with the CDIO Standards and contribute to the advancement of engineering education. Through a compact overview of literature and an analysis of two comparative educational models, this paper aims to redefine the educational approaches to failure, positioning it as a catalyst for creativity, learning, and innovation in engineering.

## METHODOLOGY

This study employs a qualitative approach using different methods to explore the manifestation of learning from failure in two distinct design education settings at an engineering university in Singapore. The methodology is designed to capture a holistic understanding of first-year undergraduate students' experiences in two different design thinking courses: a semester-long, compulsory Design Thinking and Innovation Course (henceforth DTI) followed by approximately 400 students; and a one-week, optional cross-cultural design thinking program (henceforth CC) followed by 19 of our students. The participants consisted of undergraduate engineering students enrolled in the semester-long course DTI, which was structured around a main design challenge on the topic of light and a series of workshops and classes, and/or in the intensive one-week program CC that focused on cross-cultural team-based design projects. The selection of these courses for comparison was intentional, providing a contrast not only in duration but also in the cultural and collaborative dynamics central to the design thinking process.

Data was gathered through a combination of observations, semi-structured interviews, and student reflections (e.g. Ybema et al., 2009; O'Reilly, 2005), with the main aim to capture and understand students' experiences when facing setbacks and what strategies they then employ. Observational data was collected by the research team, which attended course sessions and documented student interactions, their responses to design challenges, and instances of failure and subsequent iteration. Interviews were conducted with a sample of 12 students. We selected students who followed both DTI and CC to allow for more meaningful comparison between the two courses and to represent a range of experiences and perspectives. Each interview lasted for 60-90 minutes. These interviews probed deeper into students' perceptions of failure, their emotional and cognitive responses to challenges, and the learning they derived from these experiences. Student reflections were gathered only from the students participating in the CC course, and these were administered through online reflective journals and feedback forms. In these reflections, students were asked a number of open-ended questions about their experiences and challenges faced, providing a first-person account of their learning journey and the role of failure within it.

The qualitative data from observations and interviews were coded using thematic analysis (cf. Glaser & Strauss, 2006), with an initial coding scheme developed based on the theoretical framework of learning from failure. The coding process was iterative, allowing for new themes related to failure and learning to emerge from the data (Table 1). When analyzing the data we kept our broad exploratory question in mind of how students experience and encounter failure in their work. Hence, our data revealed different dimensions of how students themselves define what it means to fail in their schoolwork, as well as the different types of failure they encounter. In Table 1 we present these themes with more detail, and we elaborate on these in the findings section.

All participants were informed of the study's purpose and provided consent prior to data collection. Ethical guidelines were strictly adhered to, ensuring confidentiality and the right to withdraw from the study at any point. The research design was reviewed and approved by the university's Institutional Review Board.

The methodology of this study is rooted in a comprehensive approach to understanding learning from failure in engineering education. By employing a mixed-methods design, the research captures a rich and detailed portrait of the student experience, offering insights into how pedagogical strategies can be optimized to enhance learning and innovation in design thinking courses. The subsequent findings section will detail the results of this methodological inquiry, presenting the key insights derived from the comparative analysis.

Table 1. Thematic Analysis of the Raw Qualitative Data

| Raw Qualitative Data (Examples) | Sub-theme | Theme |
|---|---|---|
| Used the wrong orientation of the cardboard so that the chair is fragile, cannot stand | Incidental failure | Type of failure |
| Sensors were installed in the wrong location, so that the lights were not on when users waved their hands | Incidental failure | Type of failure |
| Wrong match of wires and batteries, small explosion and damage | Incidental failure | Type of failure |
| Tried different materials for testing, some materials didn't work or didn't meet the team's expectations | Iterative failure | Type of failure |
| Tried different structures for testing, some structures didn't work or didn't meet the team's expectations | Iterative failure | Type of failure |
| Instructors let students try to solve problem without lecturing first. While students failed, instructors served as a facilitator to help students out. | Intentional failure | Type of failure |
| Time constraint, so that students need to do rapid prototyping | Intentional failure | Type of failure |
| Material constraints, so that students need to iterate from low-fidelity materials. | Intentional failure | Type of failure |
| Create "safe-to-fail" learning environment; Classroom culture of "embracing failures" | Intentional failure | Type of failure |
| Not innovative; already exist in the market | Not innovative | Definition of failure |
| The design doesn't solve problem; Failure would be when our prototype does not function as we wanted it to be | Bad function | Definition of failure |
| The design does not satisfy me; didn't meet our expectation; The idea does not work as it should be | Does not meet expectation | Definition of failure |
| Team disagreement; not everyone contribute to the project | Team disagreement | Definition of failure |
| Something that can be improved; learning process; Earlier fail earlier problem solve | Learning process | Definition of failure |

## FINDINGS

DTI is a one-semester compulsory course for the first-year engineering students in a Singaporean university. The course uses a double-diamond design framework to facilitate divergence and convergence, in which students are asked to identify a problem in a specific geographic area in Singapore and how they can address or solve this problem through the use and design of 'light'. The problem is unknown and the solutions are unknown. CC is a one-week summer cross-cultural design thinking course where Singaporean students travelled to an Indonesian university and teamed up with Indonesian students to design a transformative chair with cardboards. See Table 2 for an overview of the different characteristics of both programs.

Table 2. Information DTI and CC

| Aspect | Semester-Long Course DTI | One-Week Program CC |
|---|---|---|
| Duration | Full semester | One week |
| Focus | Sustained engagement, in-depth exploration | Intense, rapid problem-solving |
| Cultural Context | More homogenous | Cross-cultural teams |
| Types of Failure | Incidental, Iterative, Intentional | Incidental, Iterative, Intentional |
| Learning from Failure | More structured, incremental | Immediate, adaptive |
| Pedagogical Approach | Iterative learning with multiple feedback loops | Fast-paced, with a focus on quick iteration |

***Types of Failures***

*Incidental Failure*

In the design process, some failures are unforeseen and incidental. Therefore, students need to think about how to solve these unavoidable and sudden failures. For instance, in the following example, during the design process, students did not notice the characteristics of the cardboard they had to work with. When making transformative chairs out of cardboard in CC, there were some inevitable challenges or difficulties, such as how to make use of the orientation of the cardboard to make the design more robust or to make the chair stronger. Otherwise, it could easily collapse or become fragile. As one student mentioned:

“We didn't even notice the orientation on the cardboard, so the structure we started with was weak and couldn't stand up.”

The second example shows incidental failures encountered by students during the installation of sensors. In DTI, students installed sensors on fixtures of their own design, allowing users to interact with the fixture by waving their hands or making other hand motions. However, if the sensors are installed incorrectly or if other materials interfere with the sensors, the lamp will not light up or the design will fail (see next quote and Figure 1):

“Before the team presentation, we tried out our equipment, and all of a sudden we waved, but the lights wouldn't come on, and we were annoyed at how suddenly they didn't come on. We were annoyed that it suddenly didn't work. However, we took the time to check the problem, because the glass cover on the outside was affecting the sensitivity of the sensor.”

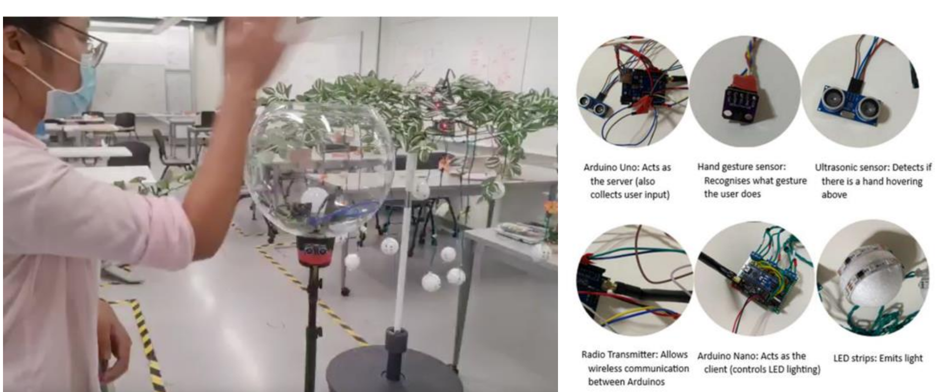


Figure 1: Encountering Incidental Failure in Design

These incidental failures require students to overcome difficulties, find solutions by themselves, and increase their failure tolerance and resilience during the design process.

*Iterative Failure*

In the Design thinking course, students constantly explore better solutions or designs through iteration. They tried different structures and materials to achieve the desired effect. For instance, Figure 2 shows students' iterations of a structure designed to ensure more social interaction from users' perspectives and for reducing manufacturing cost of the structure.

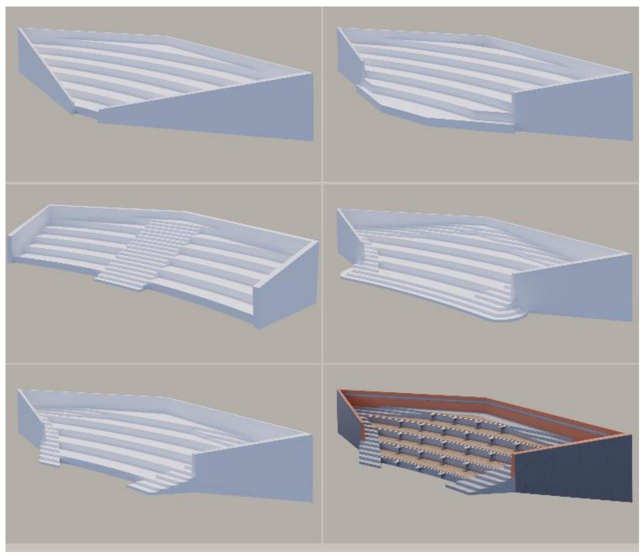

Figure 2. Design Iterations of Structure

Students considered the following while navigating these different iterations:

"User feedback showed that the small entrance made the space feel claustrophobic. The large steps did not align with BCA guidelines for stairways. Later iterations varied the barrier length, angle and height as well as adding approved stairs and handrails in varying locations."

Figure 3 shows the iterative sketches during students' design of CC. The image on the left one shows the iterative sketches of a chair in the shape of accordion, while the right two images show the iterative sketch of other chairs designed by different teams. Noteworthy, students highlighted the role of sketching here as a catalyst for rapid iteration and in coming to more creative designs:

"We were inspired by the accordion to create a chair that stretches and shrinks like an accordion. We repeatedly iterate, through many unsuccessful attempts."

"When we sketch, we keep iterating on our concept."

Figure 3. Iterations of Chairs in CC

*Intentional Failure*

In both courses, the instructors let the students try on their own, while the instructors act as facilitators to nudge the students to keep trying. When students found that a particular solution did not solve the problem, they looked for the cause and asked the instructors for advice. This intentional failure is a kind of instructors' way of teaching, not unlike ‘Productive Failure’, in which the students first try on their own, and then through the instructor's explanation acquire a deeper understanding of the knowledge. This thus suggest that instructors can play an active role in helping students encounter and learn from failure in the design process, and that the specific ways in which this is done may contribute to the development of a growth mindset and potentially more creative output. We also found examples of teachers creating a friendly “safe-to-fail” environment to let students try boldly and embrace upcoming failures.

Furthermore, when interviewing students, many of them mentioned time constraint and material constraint while talking about the difficulties and challenges they encountered. In fact, some of these constraints were intentionally built in by instructors. For instance, “time constraint” in DTI, to encourage rapid prototyping; or “material constraint” in CC, so that students need to start with “low fidelity” and iterate more.

***What DTI Can Learn From CC***

Below (see Table 3), we compare several themes that emerged from our findings as being significant in the design thinking process. They also appeared differently in both courses, allowing us to zoom in on their effects on the potential to learn from failure.

Table 3. Comparison of the Two Courses

| | One-semester DTI | One-week CC |
|---|---|---|
| Theme | Glow (Lights instalment and social interaction) | Configurable Chair with Cardboard |
| Team | 4-5 Singaporean students | 2-3 Singaporean students and 2-3 Indonesian students (Business & Management) |
| Graded | Yes | No |
| Reflection | No | Yes |
| Number of Iterations | More | Less (Time constraint, material constraint) |
| Feedback in class | Two instructors from different backgrounds in each class (engineering and architecture) | Two engineering instructors for the whole program |

*Grading System*

In our interviews with students, students in DTI tended to choose safer design solutions because they wanted to secure their grades. The students followed the rubrics given to them by the teacher and followed the criteria of what is achievable. Particularly in Asia, students are trained for a long period of time to "take tests" before entering university, as well as in the educational culture of their schools and families (Wong, Kwek & Tan, 2020). Often, scores or GPAs are perceived to be more important than the learning process itself. Although the DTI course is not based on traditional exams and is project-based learning, most of the mindset for these first-year students is still based on grades. As long as there are grades, it will have an impact on the students, including the interaction between team members.

"Our team members have some novel ideas, but we feel it's risky, and if we don't achieve them, we'll get a low grade, and we won't have time to start all over again. "

"I still care about my GPA, because it's what I look at when I'm looking for a job, and it's what I look at when I'm applying for my master's. It's a baseline. I know design students look at profiles, but GPA is the baseline."

These quotes show that students care about their grades. They want to secure their grade for their future work-transition or further degree application. If they choose innovative ideas, they are not sure whether they will be able to achieve it at the end of their semester because grades are mainly based on the outcomes. While the process of exploring the novel and creative ideas may be fun to students, this process is not graded or evaluated.

The CC programme, on the other hand, is a cross-cultural summer trip based on an intensive design thinking course, and because it is non-graded, design ideas are varied, e.g., Indonesian cultural elements are incorporated. The team members are more willing to try out ‘risky’ ideas or new ideas.

"Compared to DTI, we felt a lot more relaxed because, firstly, we were more familiar with the methodology as we had taken a semester of design thinking course compared to Indonesian students, and secondly, we were more willing to take risks and try out new ideas because it didn't matter if we failed, and it didn't have any effect on our GPA."

Through this comparison, we see that the grading system and rubrics of design projects matter. If innovation is indeed a key learning goal of such projects, the process besides just outcome should be measured. Since students attach great importance to grading, it is very difficult to change the students' mindset within a short period of time because it is closely relates to the social environment, family education, and the basic education system in a country. Therefore, instructors can consider taking measures to see how students' design and learning process can be evaluated, for instance, via peer feedback, peer evaluation, or rating from external industry people. The revised grading system should be able to encourage students to try out creative ideas, even if they fail, but the process is meaningful and worth trying.

*Teamwork (Interdisciplinary, cross-cultural, labour distribution)*

We found that teamwork in the DTI course was a huge challenge, and that many problems arose during a semester of collaboration. Due to different perspectives, different habits of working, and different personalities, students found that teamwork presented many problems.

"We had a hard time working together as a team because some students were very reluctant to co-operate and always talked about things on paper and didn't do anything concrete, which caused us a lot of headache."

In the CC programme, half of the students from Singapore, who had already attended the DTI course, and the other half from Indonesia, majoring in Business and Management, worked well together. Basically, the Singaporean students took the lead, played the role of facilitator in the team, and were better at drawing diagrams. The Indonesian students were better at product marketing in Design Thinking and incorporating Indonesian culture into their designs.

"We had a great time working together as a team during the CC programme, probably because we were all from different partner institutions and it was only a week long. But I think it was also because we complemented each other and had a clear division of labour. "

Based on this comparison, a teamwork workshop for DTI students would be an educational intervention to enable students to understand how to work effectively in a team, and divide the workload according to the skills that the team members are good at.

*Reflection*

During the CC programme (because it is a non-graded program), the researchers were able to pilot with an educational interview - integrated reflective practices - by asking students to fill out Google Forms to record their reflections. Reflection questions included: What are main difficulties/challenges you encountered during this furniture design project? How did you respond to these difficulties/challenges? In future, if you encounter such difficulties/challenges again, what will you do differently? and so on.

While answering the question: “In the future, what will you do if you encounter such difficulties/challenges again?”, students mentioned the following:

- Abandon idea and think of a different one.
- Plan ahead and set daily/per-session goals.
- Do some research in advance.
- Try iterations with smaller pieces before committing to the final prototype.
- Prepare a script or learn more deeply about the concept of our design.
- Plan out potential issues before making the prototype.

More importantly, when probed, students had developed new thinking around the role of failure in design thinking. They realized that “failure” is a learning process for them:

- You fail and learn at the early stage, and you can improve and continue faster to success.
- The more you fail, the more you know how to fix, that’s where improvement comes.
- Failing often is important is very helpful to create improve iterations and always brings new improvement to the design however, failing early is crucial to actually have time to improvise.
- Failing is part of the process , so we need to find other way to solve a problem that made our design is fail.

This reflective practice encouraged students to reflect on their learning process, the challenges they faced, and how they overcame them. It enabled students to learn from the process and learn from their failures.

***What CC Can Learn From DTI***

*More Open Themes Encourage Innovation*

The theme of the DTI course is for students to find a problem with the theme of “lights” and explore how they can stimulate social interaction through light installation, while the theme of the CC program is to design a transformative chair using cardboard. DTI has a more open theme, allowing students to find problems and explore unknown solutions to the complex problems in the real world, and to realise social innovation by offering different solutions, not limited to an engineering product design.

Because engineering problems nowadays are becoming more and more complex, choosing a real-world complex topic for engineering students can help students appreciate the journey of problem solving and exploration. Furthermore, problems that are socially relevant or have a direct impact on communities can be particularly engaging. Lastly, solving the real-world complex engineering problems requires interdisciplinary knowledge and skills. It is important to encourage students to draw on knowledge and methods from different disciplines. This can help them think outside the box and find innovative solutions that might not be apparent when viewing the problem from a single perspective.

*Increase the Frequency of Iteration*

DTI is a one-semester course based on a two-diamond framework that allows students to complete team-based projects. Through a process of Divergence and Convergence, iteration after iteration is accomplished. The teacher encourages students to explore more and encourage different ideas during the process. One student, in comparing DTI and CC:

“None of our Indonesian students had a background in design thinking, but we had a full semester of the course, especially the training for iteration, so we repeatedly emphasised iteration and the need to keep trying to come up with a better solution.”

“For us Singaporean students, CC programme was like an opportunity for rapid prototyping. Due to the short time frame, we did not have enough time to follow the Double Diamond framework. It is more like a one-week rapid prototyping activity.”

*Interdisciplinary Context*

In the DTI, each class is taught by two teachers from different backgrounds, one from engineering and one from architecture. During the design process, the two teachers often have different types of feedback for students, reasoned from their different areas of expertise. This was hard for students but encouraged their thinking across disciplines:

"We were confused at first, because we asked different teachers, and they gave us different advice. Then the teacher told us that we were simulating the real design environment, and that different stakeholders might have different suggestions, so that we could think about how to solve the different feedback by ourselves, so that the design could be more creative and meet the needs of different stakeholders. "

Therefore, during the one-semester design process at DTI, the student received advice from both teachers from different perspectives. Thus, students kept iterating while receiving and incorporating this feedback into their design.

## CONCLUSIONS

The comparative study of DTI and CC at an engineering university in Singapore offers insights into the dynamics of learning from failure in engineering education. Drawing on Amabile's (1988) dynamic model of creativity and innovation, this exploration underscores the necessity for adaptable and context-sensitive pedagogical approaches.

Our study delves into the diverse types of failures encountered by students, aligning with Clifford's (1988) discussion on failure tolerance and extending it to the multifaceted context of engineering design. Specifically, it contributes to recent work on the role of learning from failure as a specific pedagogy that can enhance the learning of engineering students in diverse ways, such as promoting a better understanding of safety (Cheah, 2023) or generating a greater appetite to experiment, take risks and innovate (Foley, Foley & Kyas, 2022; Huang et al., 2023). This further contributes to the broader discourse on culturally aware pedagogies, echoing Kim's (2005) emphasis on the influence of cultural dynamics in learning. Table 4 summarizes these types of failure, each eliciting different responses and adaptations from students, thus contributing to their learning journey in unique ways.

Table 4. Interpretation of Types of Failure Encountered

| Type of Failure | Description | Learning Experience |
|---|---|---|
| Incidental | Unforeseen challenges that prompt immediate problem-solving | Develops quick-thinking, adaptability |
| Iterative | Emerges from the design process; trial and error | Enhances resilience, understanding of design process |
| Intentional | Introduced by educators as learning opportunities | Encourages risk-taking, exploration of new ideas |

Our findings challenge the traditional 'Productive Failure' model, proposing a more dynamic framework suitable for the complex, solution-varied world of engineering. This aligns with Tawfik, Rong, and Choi's (2015) call for failure-based learning designs that foster creativity and problem-solving. Our study makes specific contributions to existing literature by demonstrating empirical evidence of diverse learning outcomes from different approaches to failure in engineering education. This research extends the conversation about failure in learning, emphasizing its role as a catalyst for innovation and creativity.

In conclusion, this research underscores the importance of failure as a vital component of the learning process in engineering education. It advocates for a pedagogical shift that values learning from failure, aligning with the evolving needs of the engineering industry. The insights from this comparative study highlight the need for educational strategies that are not only robust and adaptive but also capable of transforming failure into a stepping stone for success. The study's contributions to the field of engineering education are significant, advocating for strategies that foster creativity, resilience, and innovative thinking, thereby preparing students for the unpredictable and multifaceted challenges of the engineering profession.

Specifically, this study has the following implications for engineering educators, primarily centred around CDIO Standards 5 and 7. First, when integrating design thinking into engineering education students need to be nudged in the process to keep trying, keep iterating, as a precondition for being innovative. Second, create a classroom environment that embraces failures, create a safe-to-fail classroom culture, encourage students to learn from failures, try boldly and iterate in the process. Third, adopt a "student-centred" teaching concept in the classroom, allowing students to explore and solve an open-ended real-world complex problem on their own, by facilitating and inspiring students to further explore and iterate when they fail. Fourth, to incorporate grading measures of process into the grading system. For example, through peer feedback/evaluation, and ratings from external industry people. This to enhance the iterative process and encourage creativity. Finally, to develop students' teamwork ability, which is a very important soft skills for future engineers, so that students will realise how to make use of team members' respective strengths and contribute to team projects responsibly. Team diversity here leads to greater divergence of ideas and exploration of innovative ideas.

Encouraging iteration and learning from failure directly supports Standard 5's emphasis on practical learning experiences, as students are more likely to engage deeply with the design-build-test cycle when they are not afraid to fail. Adopting a student-centred approach and focusing on real-world problems aligns with Standard 7's goal of integrated learning, as it facilitates the application of interdisciplinary knowledge.

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## BIOGRAPHICAL INFORMATION

***Thijs Willems*** is a Research Fellow at the Lee Kuan Yew Centre for Innovative Cities (LKYCIC). He is an organizational ethnographer and generally interested in the daily work of people in complex and technological organizations, as well as how they experience their work in the broader organizational context. In his work, he draws on rich, ethnographic empirical data analyzed via practice and process theories.

***Qian Huang*** (Cathy) is a Research Fellow at the Lee Kuan Yew Centre for Innovative Cities (LKYCIC). She is part of the research team for the project titled "How the lightbulb was invented: Sparking creativity with 'deliberate- learning-from-failure' interventions". Her work examines how engineering graduates develop resources and capitals to manage their work transition after studying abroad.***Ameek Kaur*** is a Research Fellow at the Lee Kuan Yew Centre for Innovative Cities (LKYCIC). She is part of the team for the project "How the lightbulb was invented: Sparking creativity with 'deliberate- learning-from-failure' interventions" project. Ameek's career trajectory has evolved through the domains of Engineering, Innovation, and Management. She has worked as an Engineer, Educator, and a Researcher.

***King Wang Poon*** is the Director of the Lee Kuan Yew Centre for Innovative Cities (LKYCIC) where he also heads the Smart Cities Lab and the Future of Digital Economies and Digital Societies initiative. With his multi-disciplinary team, the research focuses on the human dimensions of smart cities and digital economies, and the impact of digital transformation on the future of work, education, and healthcare, and on society at large. He pays particular attention to how leaders of cities and companies can design strategies and policies to lift the lives of their citizens and workers, with the same technologies that are disrupting work, economy and society.

***Corresponding author***

Thijs Willems
Singapore University of Technology and Design
Lee Kuan Yew Centre for Innovative Cities 8 Somapah Rd, Building 3, Le-vel 2
487372 Singpore, SINGAPORE
thijs_willems@sutd.edu.sg