CULTIVATING SUSTAINABILITY MINDSETS IN MECHANICAL ENGINEERING EDUCATION THROUGH DESIGN-IMPLEMENT EXPERIENCES

Kim-Fai SOH

School of Mechanical and Aeronautical Engineering, Singapore Polytechnic

Sin-Moh CHEAH

Department of Educational Development, Singapore Polytechnic

ABSTRACT

This paper presents a comprehensive framework for cultivating sustainability mindsets within mechanical engineering education at Singapore Polytechnic through the integration of the CDIO (Conceive-Design-Implement-Operate) approach. Recognizing the urgent need for engineers to move beyond technical proficiency toward sustainable innovation, the initiative addresses the recurring challenge of limited value internalization, where students understand sustainability concepts but fail to act upon them. The proposed strategy employs the CDIO design-implement experiences structured around three vertical "pillar" courses – *Introduction to Engineering* (Year 1), *Design & Implement* (Year 2), and *Capstone Projects* (Year 3) – to progressively embed sustainability principles across the curriculum. These experiences are aligned with selected UN Sustainable Development Goals and guided by Isabel Rimanoczy's Sustainability Mindset Principles (SMPs), which emphasize cognitive, behavioral, and affective dimensions. Complementing these principles, the framework prioritizes two dominant Key Competencies for Sustainability (KCS) – Integrated Problem-Solving and Systems Thinking – while weaving in transversal competencies. Implementation plans for Year 1, and Year 2 illustrate how sustainability can be infused into cornerstone and intermediate projects through activities such as carbon footprint analysis, closed-loop system design, and reflective strategy proposals. The double-helix curriculum model highlights the interplay between SMPs, KCS, and SDGs, ensuring that sustainability is not treated as an elective theme but as a core pedagogical spine. By embedding sustainability into authentic design-implement experiences, the framework aims to transform student attitudes, foster ecological accountability, and prepare graduates to design resilient, circular, and socially responsible systems. Future directions include longitudinal studies to evaluate the impact of this model on students' professional identity formation and their ability to internalize sustainability values at both awareness and practice levels.

KEYWORDS

Sustainability Mindset, Key Competencies for Sustainability, Double-helix Curriculum, CDIO Standards 3, 5, 7

INTRODUCTION: ROLE OF MECHANICAL ENGINEERING EDUCATION IN SUSTAINABLE DEVELOPMENT

Sustainable development within polytechnic education entails cultivating the knowledge, skills, and attitudes necessary for graduates to contribute meaningfully to society. At the Singapore Polytechnic (SP), the Common Core Curriculum (CCC) provides students with a broad foundation for developing baseline emerging digital and human skills in students through the lens of the United Nation Sustainable Development Goals (UNSDGs), fostering awareness of real-world issues and their societal impacts (Cheah *et al*, 2022). While effective in building foundational understanding, these courses primarily operate at an introductory and awareness level. As noted by Alhasanni *et al* (2025):

> Engineers play a critical role in contributing to sustainable systems and infrastructure, they must be equipped with robust sustainability competencies. Further, integrating sustainability topics within the curricula should not just be surface level, but should go beyond to incorporate the transformative shift in pedagogical strategies, curriculum design, and institutional priorities. (p.2)

Within the School of Mechanical and Aeronautical Engineering (MAE), UNSDGs 3 (Good Health and Well-Being), 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), and 13 (Climate Action) are identified as most relevant to the mechanical engineering discipline. In the Diploma in Mechanical Engineering (DME), sustainability concepts are embedded through domain courses, electives and specialization courses. A summarized program structure of DME is as shown in Figure 1.

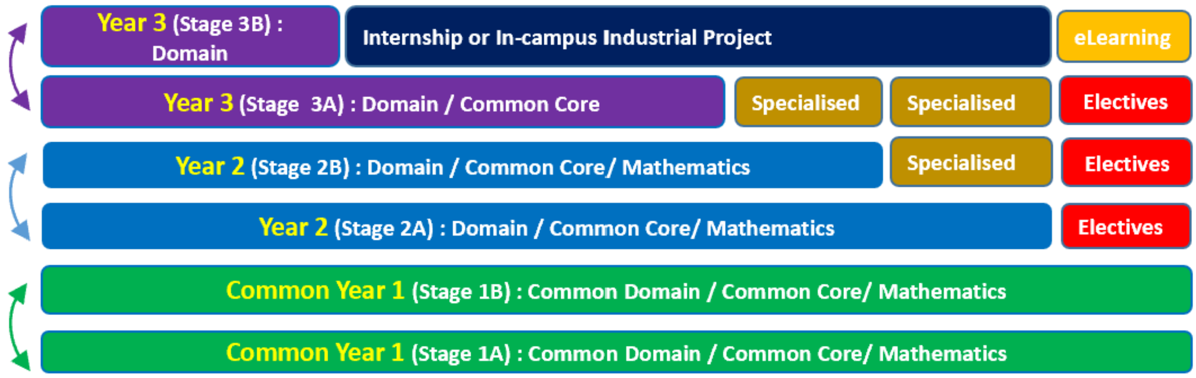

Figure 1. Program structure of DME

Despite this structured integration, a persistent challenge remains as students often demonstrate conceptual understanding of sustainability without translating it into meaningful action, reflecting limited internalization of sustainability values. Addressing this gap requires a more holistic pedagogical approach. The adoption of the CDIO (Conceive–Design–Implement–Operate) framework offers a robust foundation for outcome-based, authentic, and project-based learning around the full lifecycle of real-world products, processes, and systems. Cheah *et al* (2025, p24) pointed out that "CDIO Framework enable us to arrive at a plausible approach to integrate sustainable development into any educational program; by leveraging on the context-independence nature of key competencies for sustainability that "translate" (via the CDIO Standards) the more generic competencies (from the CDIO Syllabus) into context-specific scenarios where disciplinary knowledge is used alongside skills and attitudes to address sustainability issues". Azrai *et al* (2024, p323) concluded that "Project Based Learning models are effective in improving the pro-environmental behavior of high school students. Students can take actions that are useful for the environment using a project-based learning model, so their pro-environmental behavior increases.”. This was further supported by Ayerbe et al (2024) who noted that:

> Project-based learning was shown to be an effective methodology for increasing environmental awareness in the participating students within the context described in this study, the environmental project was particularly effective in improving the affective dimension of environmental awareness.....Moreover, the project was quite effective in increasing the level of environmental literacy, an aspect linked to high levels of awareness. Therefore, the application of environmental projects is presumed as an effective educational strategy to increase attitudes of an environmental nature that are considered essential in the current global crisis. (p.16)

Scope of this Paper

This study explores how the DME curriculum systematically inculcates sustainability mindsets through a “project” spine of 3 Design-Implement Experiences (CDIO Standard 5): one in each year of study, via selected courses (Year 1: *Introduction to Engineering*, Year 2: *Design & Implement*, Year 3: *Capstone Projects*). The “project” spine features an Integrated Curriculum (CDIO Standard 3) addressing selected UNSDGs using the 2 key competencies for sustainability (integrated problem-solving and systems thinking) intertwined as a double-helix supported by other key competencies. The implementation plan for Years 1 and 2 are shared; and future directions, including plan for longitudinal studies to assess the impact of the proposed framework on students’ attitudes and value internalization at both awareness and professional levels, are shared.

DIPLOMA IN MECHANICAL ENGINEERING (DME) IN SINGAPORE POLYTECHNIC (SP)

A Short Summary of DME

The Diploma in Mechanical Engineering (DME) as shown in Figure 1 is Singapore’s first engineering program, providing a solid foundation in mechanical engineering since its inception in 1958. Current annual students’ intake is about 220 and they will undergo a three-year program with a common first year shared between Diploma in Aeronautical Engineering and Diploma in Mechatronics & Robotics. The program utilizes a swapping model, except for Mathematics and certain CCC courses, which follow a sequential structure. In a swapping model, courses across each year of study are organized into two stages. For instance, in Year 1, courses are assigned to either Stage 1A or Stage 1B. First-year students are divided into two groups, with one group commencing their studies with Stage 1A courses in the first semester, while the other group starts with Stage 1B courses. In the second semester, the groups swap stages. This swap model addresses resource/ facilities optimization, ensure relevant courses are gathered within the same stage, maintaining good staff to student ratio (1:20) and ensuring good study load balance.

The DME curriculum offers 6 specialization groups namely: (1) Automation & Robotics, (2) Energy & Facilities Management, (3) Engineering Design & Simulation, (5) Biomedical, (5) Precision Engineering and (6) Rapid Transit Technology. Each group has 3 specialized courses. Students in DME are to select one specialization from second year onwards. Students will be paired to relevant companies (for internship) or industrial projects based on their specializations. Teaching and learning are based on the CDIO Framework enhanced with design thinking methodology. Instructions are delivered through a blend of online asynchronous lectures, in-person tutorials, and practical sessions for the majority of domain courses. Projects (CDIO design-implement experiences) is the dominant method of engaging students in learning.

Mapping UN SDG for DME

An exercise was mandated in SP for all programs to carry out mapping of the courses against relevant UNSDGs. The outcome for DME is shown in Table 1, for core courses and CCC courses. Servicing courses in other departments such as electrical and electronics and mathematics are not included in the mapping.

Table 1. Mapping of DME with UNSGDs

	Course Title	United Nations Sustainable Development (UNSDG) Goals					
		3	7	9	11	12	13
		Good Healthy and Well Being	Affordable and Clean Energy	Industry, Innovation, and Infrastructure	Sustainable Cities and Communities	Responsible Consumption and Production	Climate Action
Y1 - S1	Computer Aided Drafting						○
	Thermofluids 1		◉				
	Mechanics 1						
	CCC- Thinking Critically about the UN SDG	◉	◉	◉	◉	◉	◉
	CCC- Data Fluency	◉	◉	◉	◉	◉	◉
	CCC- Digital Communication for Impact	◉	◉	◉	◉	◉	◉
	CCC- Collaboration in the Digital Age						
Y1 - S2	Introduction to Engineering	◉		◉	○	◉	○
	Engineering Materials 1	○	○	◉	○	◉	○
	CCC- Problem Solving with Creative & Computational Thinking	◉	◉	◉	◉	◉	◉
	CCC- Effective Writing for the Workplace	◉	◉	◉	◉	◉	◉
	CCC- Persuasive Communication with Data Storytelling	◉	◉	◉	◉	◉	◉
Y2 - S1	Thermofluids 2		◉				
	Mechanics 2						
	Engineering Materials 2	○	○	◉	○	◉	○
	Computer Aided Machining		○	◉	○	◉	○
	CCC- Artificial Intelligence & Its Impact	◉	◉	◉	◉	◉	◉
Y2 - S2	Design and Build		◉	◉	○	◉	○
	Industrial Automation	○	○	◉		○	○
	CCC- Sustainable Innovation Project	◉	◉	◉	◉	◉	◉
Y3 - S1	Engineering Thermodynamics		◉	◉	○	○	○
	Mechanics 3						
	Fluid Mechanics						
	CCC- Personal Branding and Career Agility	◉	◉	◉	◉	◉	◉
Y3 -S2	Internship	◉	◉	◉	◉	◉	◉
	Industrial Project	◉	◉	◉	◉	◉	◉
	Workplace Safety & Health Management	◉					
Specialisation courses	Mechanical Assembly Design in CAD		○	◉	○	◉	◉
	Manufacturing Processes with Design for Manufacturing		◉	◉	◉	◉	◉
	Engineering Simulations		◉	◉	◉	◉	◉
	Refrigeration & Air-conditioning		◉	◉	◉	◉	◉
	Renewable Energy & Applications		◉	◉	◉	◉	◉
	Building Information Modelling for MEP Services		◉	◉	◉	◉	◉
	Digital Fabrication and Metrology		◉	◉	○	◉	○
	Multi-Axis Machining Applications		○	◉	○	◉	○
	Tooling Engineering		○	◉		◉	
	Railway Systems		◉	◉	◉	◉	◉
	Rolling Stock Design & Maintenance		○	◉	◉	○	◉
	Railway Infrastructures Design & Maintenance		○	◉	◉	◉	◉
	Smart Solution Development		◉	◉	○	○	○
	Robotics for Advanced Manufacturing		◉	◉	◉	◉	○
	Programmable Logic Controller						
	Assistive Technology & Rehabilitation Engineering	◉					
	BioMechanics						
	Biofluids						
	Contamination Controls & Clean Room	◉	◉	◉	◉	◉	○
Electives	Fundamental of Composite Repairs		○	◉		◉	◉
	Quality Engineering and Management		○	○	◉	◉	○
	Industrial Engineering		◉	◉		◉	○
	Introduction to Additive Manufacturing [3D Printing]		◉	◉	○	◉	○
	Introduction to Cobot		◉	◉	◉	◉	○

From Table 1, we note that DME has a good spread of mechanical courses with the potential of infusing sustainability topics. Bold circle “◉“represents greater ease of infusing the relevant

UNSDG into the course, based on current learning activities and objectives. A light circle “O“ represents “somewhat” feasible. CCC courses cover the UNSDGs well as most are designed to bring out the awareness of UNSDG. The 9 mechanical courses highlighted are those that are currently infused with sustainability topics. Their respective topics are shown in Table 2. Many of these topics are implemented by hands-on activities or assignments using CDIO Standard 7 (Integrated Learning Experiences and CDIO Standard 8 (Active Learning).

Table 2: Courses with sustainability topics interwoven around the 3 “pillars”

	Course	Topics for sustainability development	UN-SDG
1	Mechanical Assembly Design in CAD	Circular economy topics for design for assembly	9,12,13
2	Manufacturing Processes with Design for Manufacturing	Circular economy topics for selecting manufacturing process	7,9,11,12,13
3	Air-conditioning and Refrigeration	Touch on Green Marks in the application and ways for better energy efficiency	7,9,11,12,13
4	Renewable Energy & application	Methods for renewable energy application and design.	7,9,11,12,13
5	Building Information Modelling for MEP Services	Touch on Green Marks and energy management	7,9,11,12,13
6	Engineering Thermodynamic	Topics on energy saving	7,9
7	Engineering Material 2	Recycling of material in the various processes?	9,12
8	Fundamentals of Composite Repair	Recycling of composite of materials and new development in sustainable resin.	9,12,13
9	Quality Engineering and Management	Environmental and Sustainability Management (ISO 14000/Environmental Impact Study/Hazardous Waste Management	11, 12

THE DME CURRICULUM REVAMP APPROACH

We noticed most of the 9 mechanical courses infused with sustainability topics are either elective or specialization courses. This implies that some students from the same cohort may not have sufficient “touch points” of training in sustainability mindset development. We need to ensure at least 1 “pillar” course with CDIO Standard 5 (Design-Implement Experiences) covered in every year of study, interwoven with other courses with sustainability topics. For effectiveness in transforming behaviors and attitudes using design-implement experiences, we also need to explore relevant sustainability mindset principles and key competencies for sustainability.

Sustainability Mindset Principles

Rimanoczy (2019) conceptualized a set of 12 Sustainability Mindset Principles (SMP) which encompasses three perspectives – cognitive, behavioral, and affective. These dimensions guide the pedagogical design of learning experiences that promote sustainability beyond technical awareness. The 12 Sustainability Mindset Principles (SMP) are organized into four domains: Ecological Worldview, Systems Perspective, Emotional and Spiritual Intelligence as shown in Figure 2.

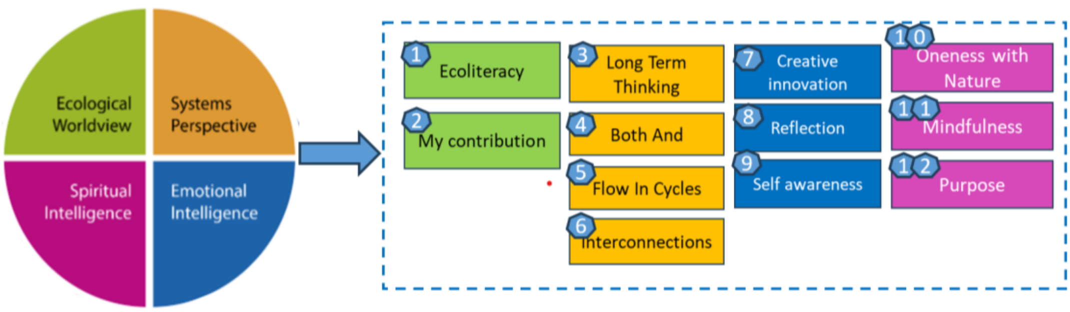

Figure 2. Sustainability Mindset Principles (SMP)

These principles explicitly define the mindset components essential for integrating sustainability into the core phases of design-Implement experiences. Key SMPs that can be actively cultivated include:

- Long-term Thinking (Principle 3): Students learn to consider that every action has consequences that are not immediately visible and that analyzing situations based on the long term has a positive impact on global sustainability.
- Both-and Thinking (Principle 4): This perspective allows students to understand paradoxes and calls for creative solutions that are inclusive of all stakeholders.
- Flow in Cycle (Principle 5): This principle encourages a mindset for reuse, reduce and recycle as early as in the design phase to reduce product design obsolescence.
- Interconnectedness (Principle 6): This principle promotes developing solutions from a system perspective especially when solving "wicked" problems.
- Creative Innovation (Principle 7): This principle emphasizes that resilience is based on constant creativity, innovation, and experimentation.
- Reflection (Principle 8): Reflective practices help students pause, ponder the situation and implications before jumping into action. This is critical for evaluating long-term consequences of design choices.
- Purpose (Principle 12): Defining one's professional purpose ensures that the skills acquired are directed toward shaping a better world.

Key Competencies for Sustainability

Retaining the United Nations Educational Scientific and Cultural Organization (UNESCO) definition of key competencies for sustainability (KCS), Cheah *et al* (2025) had reconciled the discourse on what constituted key competencies for sustainability from the extant literature and formulated a model for their integration in any program as they are transversal, multifunctional and context independent. There are altogether 8 KCS to develop students' sustainability mindset: values thinking, intrapersonal, interpersonal, futures thinking, systems thinking, strategic thinking, implementation, integrated problem-solving. Cheah *et al* (2025) suggested that each program integrating sustainable development into its curriculum can customize the sequencing of the 8 KCS based on the program's own pedagogical approach. In the context of DME, we identified 2 dominant KCS that run through the entire program duration: integrated problem-solving competency and systems thinking competency.

Integrated Problem-solving Competency

As the curriculum of DME is heavily dependent on projects as the backbone, Integrated Problem-Solving Competency becomes an important feature in the curriculum planning for DME, which requires students to conceive, design, implement and operate a mechanical artefact at increasing level of difficulty over the program duration. The DME curriculum made use of 3 design-implement experiences (CDIO standard 5) in each year of the 3-year program duration using 3 "pillar" courses, starting from *Introduction to Engineering* course (with design-implement experience at basic-level supporting CDIO Standard 4) in year 1, *Design & Implement* course (CDIO Standard 5, design-implement experience at intermediate-level) in year 2 and *Capstone* (Final Year Project) course in year 3 (CDIO Standard 5, design-implement experience at advanced-level). These 3 "pillar" courses formed the "project spine" for DME's integrated curriculum (CDIO Standard 3) by partnering with other courses in the same stage to achieve larger project objectives.

Systems Thinking Competency

As project development of complex products and processes in DME consist of inter-related elements, the solution must consider the whole system and its entire life cycle. Hence, emphasis on system thinking competency is necessary. Take carbon emissions of vehicles as an example. Beyond zero-emission narratives, sustainability requires a lifecycle perspective encompassing production, usage, and end-of-life processes. Kurkin *et al* (2024) highlighted the importance of lifecycle assessment (LCA) in understanding the true environmental impact of electric and internal combustion vehicles. This comprehensive mindset extends to evaluating the social and economic impacts on environment across the entire value chain. Product design and development is an important domain in the mechanical discipline whereby systems thinking is crucial, impacting on the environment. Planned obsolescence in product development and manufacturing exacerbates environmental degradation by shortening product lifespans and increasing resource consumption, thereby underscoring the urgent need for pedagogical approaches that integrate circular economy principles and comprehensive life cycle thinking into engineering education (Guerra *et al*., 2023; Perpignan, 2021; Deng *et al*., 2021). Sierra *et al* (2023) had observed the challenges of effective strategy to reduce obsolescence which has a downstream impact on the environment. They had identified several methodological design approaches to resist or postpone obsolescence (see Figure 3). Hence, integrating real-world scenarios and hands-on projects that encourage students to analyze and optimize product lifecycles is essential for developing engineers capable of designing truly sustainable systems (Olsen *et al*., 2013). Table 2 shows some courses with sustainability topics which are currently infused into DME. Courses such as *Design for Manufacturing* and *Design for Assembly* could further contribute to students' sustainability Mindsets by including obsolescence in product design.

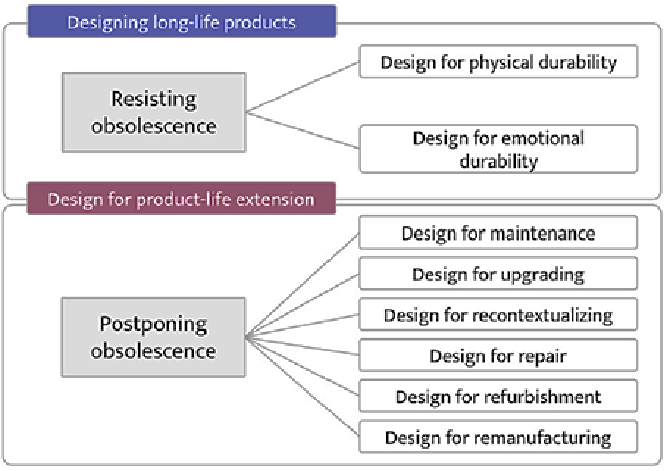

Figure 3: Resisting and postponing obsolescence in product design

DME's SUSTAINABILITY MINDSET DEVELOPMENT MODEL

The dual focus on integrated problem-solving competency and systems thinking competency led us to formulate the double helix model as the approach for DME to develop sustainability mindset in its students.

The middle of Figure 4 shows the 3 "pillars" of the DME curriculum (i.e. the 3 courses of *Introduction to Engineering, Design & Implement,* and *Capstone*) as explained in previous section. In DME, the *Capstone* course can be in-campus industrial final year project or internship at companies' premises. The left side of Figure 4 listed various KCS and the right side showed the 12 SMPs and UNSDGs to be infused into the courses where appropriate. Curriculum mapping was systematically carried out by analyzing existing courses, to identify opportunities for embedding SMPs and KCS.

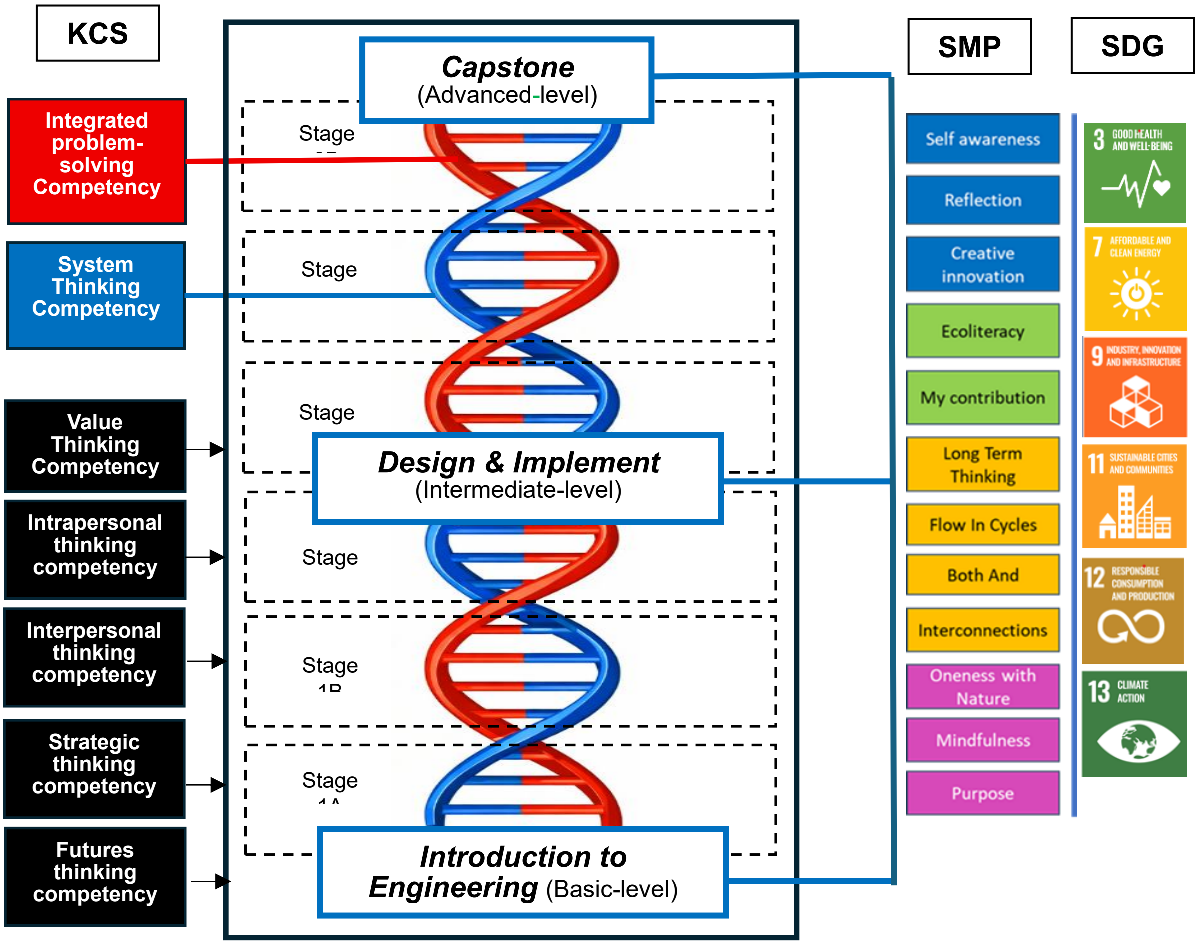

Figure 4. Double Helix as "Spine" of 2 key competencies for sustainability for DME

Values thinking will be infused during the various project activities. This is critical for students to not only comprehend environmental issues but also to develop innovative solutions and engage in reflective practices that promote long-term ecological and social well-being. Likewise other KCS will also support the development of Integrated Problem-solving and Systems Thinking Competencies.

IMPLEMENTATION PLANS FOR DME YEAR 1 AND 2

Table 3 and Table 4 showed how the 12 SMPs are mapped to the SDGs relevant to DME as explained in Table 1 and Table 2. Table 5 and Table 6 illustrate the implementation plans for the 2 "pillars" for year 1 and year 2 respectively, with activities that can be carried out in the classroom.

For year 1, the suggested learning activities are an <u>extension</u> of the existing cornerstone project by including an online case study, analyzing sustainability issues and proposing solutions during the fabrication of mechanical parts in the cornerstone project. The task is aimed at inculcating students' mindset and their values of reducing material and energy usage, promoting circular economy within engineering practices and building a culture of environmental accountability. Table 5 further provides the justifications for the selected SMPs. We note that SDG 7: Affordable and Clean Energy and SDG 11: Sustainable Cities and Communities are very specific topics and would be better covered by specialization courses in the program which is beyond the scope of this paper.

Table 3. Mapping of SMP to SDG for 1st year *Introduction to Engineering* course

	SMP 1	SMP 2	SMP 3	SMP 4	SMP 5	SMP 6	SMP 7	SMP 8	SMP 9	SMP 10	SMP 11	SMP 12
SDG 3												✖
SDG 7												
SDG 9						✖						
SDG 11												
SDG 12			✖		✖							
SDG 13	✖											✖

Table 4. Mapping of SMP to SDG for 2nd year *Design & Implement* course

	SMP 1	SMP 2	SMP 3	SMP 4	SMP 5	SMP 6	SMP 7	SMP 8	SMP 9	SMP 10	SMP 11	SMP 12
SDG 3												✖
SDG 7												
SDG 9						✖	✖					✖
SDG 11												
SDG 12	✖		✖		✖			✖				
SDG 13	✖	✖	✖					✖				✖

For year 2, the task extends the current *Design & Experiment* course with elements of sustainability by:

- Uses CAD's sustainability function to estimate the carbon emission from the project
- Calculation of carbon footprint.
- To present and reflect improvements for reducing carbon footprint.

Year 3 implementation plan is not covered in this paper because Internship and Industrial projects would depend on the industry that the students are assigned to. The students are expected to develop their competencies from their learnings in Year 1 and Year 2; and able to transfer them to the projects. As part of their final year report, students are required to write an extensive account of a proposal on sustainability for the companies; based on their observation, technical work done and on-site empathy studies.

Table 5. Implementation plan for sustainability mindset on *Introduction to Engineering*

Selected SMP	Justification (Based on DME Context)	Suggested learning activity
Ecoliteracy	This principle is essential for understanding the environmental issues in metal fabrication, such as Air Pollution from machining works, and high Energy Consumption. Goal 13: Climate Action requires workshops to lower their carbon footprint. Understanding environmental consequences contributes to meeting the learning objective of identifying environmental issues.	Carbon Footprint Awareness: Students estimate emissions associated with a specific workshop task or product component, promoting awareness of the role of energy-efficient motors and proper machine scheduling.
Long-term Thinking	This involves considering the entire environmental impact of decisions, supporting Goal 12: Responsible Consumption and Production. The goal specifically calls for sustainable practices throughout the lifecycle of products, from raw material to disposal. This thinking is formally applied through a Life Cycle Assessment (LCA), which measures a product's environmental impact from "cradle to grave".	Material Decision Matrix: Students compare different materials (e.g., carbon steel, brass, and aluminum) for a prototype, using recyclability and life-cycle impact as crucial factors alongside cost and strength.
Flow in Cycles	Recognizing that resources must operate in cycles rather than linear processes promotes a circular economy within engineering practice, supporting Goal 12. This is necessary to address issues like Coolant & Lubricant Waste and Material Waste.	Closed-Loop System Implementation: Students research and propose implementing Closed-loop Systems for the workshop, focusing on the recovery and recycling of coolants and metal chips to minimize environmental contamination.
Interconnected-ness	This involves ensuring that design and operational decisions contribute to the sustainability of the whole system, supporting Infrastructure Resilience under Goal 9. It requires designing facilities to reduce negative external impacts like vibration, noise, and heat waste on the surrounding environment.	Infrastructure Improvement Plan: Students propose design changes for the lab (e.g., layout optimization or machine placement) to reduce noise and vibration or improve airflow and lighting.
Purpose	Defining one's professional purpose ensures that the skills acquired are directed toward shaping a better world (Goal 3, 13). This aligns with the learning objective to propose strategies to mitigate the environmental impact of fabrication activities and use real-world examples to support decision-making in sustainable workshop practices.	Sustainable Strategy Proposal: Students apply sustainable development concepts to streamline fabrication in a mini-project, detailing their strategy using examples such as the reuse of aluminum off-cuts to reduce raw material orders

POSSIBLE FUTURE WORKS

This paper presented a roadmap with plans where sustainability mindset can be developed in DME students. At the point of writing, the plan has yet to be implemented in DME. Nevertheless, the proposed integration strategy in the roadmap provides appropriate "touch points" for cultivating sustainability mindsets by establishing a three-tier project vertical integration during the program duration: Basic-level or (Cornerstone) in Year 1, Intermediate-level Design-Implement in Year 2, and advanced-level Capstone in Year 3, interwoven with relevant specialization and core courses.

Table 6. Implementation plan for sustainability mindset for *Design Implement* course

Selected SMP	Justification (Based on DME Context)	Suggested Learning Activity
Ecoliteracy	This is the foundational principle of understanding the state of the planet and recognizing the complexity of how environmental challenges are linked. For mechanical systems focused on reducing high carbon emissions, this is crucial for establishing awareness, which directly underpins adherence to Goal 13: Climate Action and the broad objectives of sustainable production within Goal 12: Responsible Consumption and Production.	Reading Material & Videos: Students engage with materials to gain full awareness of the state of the planet and the specific environmental impacts associated with mechanical processes and carbon emission generation.
My Contribution	This principle identifies the ways an individual is unintentionally contributing to the problems. By reflecting on their design choices and engineering practices, students develop the necessary social sensitivity and consciousness to address their contribution to emissions, which is key for behavioral change required by Goal 13: Climate Action.	Project Report - Improvement: Students must analyze their design and propose specific steps to mitigate the identified negative contributions (e.g., reducing material waste or energy use), demonstrating a practical application for solving the problem.
Long-term Thinking	This involves analyzing situations and making decisions while considering the long term, recognizing that every action has consequences that are not immediately visible. Applying this ensures students design sustainable engineering solutions that minimize future consequences like prolonged carbon effects on the climate, supporting the objectives of Goal 12: Responsible Consumption and Production and Goal 13: Climate Action.	Project Report - Improvement: Documentation of design deliberation should explicitly detail how potential long-term consequences (like climate effects) encourage sustainable choices and the adoption of lasting engineering solutions.
Creative Innovation	Resilience and progress depend on constant innovation and experimentation, aligning directly with Goal 9: Industry, Innovation and Infrastructure. Mechanical engineers must promote technological upgrading and develop sustainable industries. This mindset enables the adoption of technologies such eco-design and additive manufacturing to reduce waste.	Carbon footprint analysis: Use sustainability function of CAD software to estimate the overall carbon emission of student's design.
Flow in Cycles	In mechanical design, this directly mandates the use of circular economy principles and life cycle analysis (LCA), which are the critical components of Goal 12: Responsible Consumption and Production.	Design selection: Students could use morphology charts to select alternative designs with including criterion such as material reuse and circular economy concepts, shifting away from linear, waste-generating processes.
Interconnected-ness	This involves ensuring that design and operational decisions contribute to the sustainability of the whole system, supporting Infrastructure Resilience under Goal 9. It requires designing facilities to reduce negative external impacts like vibration, noise, and heat waste on the surrounding environment.	Infrastructure Improvement Plan: Students propose design changes for the lab (e.g., layout optimization or machine placement) to reduce noise and vibration or improve airflow and lighting.

Table 6. (cont'd)

Reflection	Reflective practices help students to pause, ponder the situation and implications before jumping into action. This promotes critical thinking needed to ensure that calculations and design choices actively align with sustainability goals, enabling effective compliance and progress toward targets outlined in Goal 12: Responsible Consumption and Production and Goal 13: Climate Action.	Project Activities & Project Report: Dedicated time is spent evaluating the impact of calculated decisions against sustainability benchmarks, with the resulting critical insights documented in the project reflection.
Purpose	Defining one's purpose provides an unconscious compass that guides actions toward shaping a better world when grounded on higher values (Goal 3: Good health & Wellbeing). This principle encourages students to link their mechanical engineering education to the larger commitment required to achieve ambitious goals like contributing to sustainable industrialization (Goal 9: Industry, Innovation and Infrastructure) and securing a low-carbon future (Goal 13: Climate Action).	Project Report - Reflection: Students include a self-assessment on how their design choices and acquired knowledge align with their professional purpose of contributing to global sustainability.

Future research should focus on empirical and longitudinal investigations to validate the effectiveness of this framework. Specific areas for subsequent scholarly exploration include:

1. Assessing the longitudinal impacts of the multi-level project structure on student learning outcomes and the development of sustainability competencies.
2. Exploring the role of industry co-supervision and external partnerships to provide authentic, real-world contexts and enhance the practical relevance of sustainability education. This is important to the 3rd Pillar of the framework as students are either arranged for internship or to pursue an in campus industrial sponsored projects as their capstone program.
3. Examining the effectiveness of employing interdisciplinary teams and diverse pedagogical approaches, such as culturally responsive pedagogy, to foster a deeper, more comprehensive sustainability mindset. Notably, "Interdisciplinary collaboration has proven to be a transformative approach to sustainability education" (Alhassani *et al*., 2025, p9).

CONCLUSION

This paper successfully demonstrates a strategic and structured approach for inculcating sustainability mindsets within the Diploma in Mechanical Engineering (DME) curriculum using the CDIO (Conceive–Design–Implement–Operate) framework. The proposed revamp on DME aims to bring current sustainability education beyond the introductory and awareness level for deeper internalization through design and implement experiences.

The double helix model of having System Thinking and Integrated Problem-solving Competencies as the "Spine" is due to DME's emphasis in design-implement experiences. It enables a structure pedagogy progression utilizing 3 "pillar" courses at each year of study with a major design and implement experiences, to ensure continuous engagement with relevant Sustainability Mindset Principles (SMP), Key Competencies for Sustainability (KCS) and selected SDGs. Learning activities for the "pillar" courses are suggested. Holistic integration with selected Sustainable Mindset principles and UN SDGs is afforded by interweaving courses with sustainability topics around these pillars.

The paper provides a comprehensive blueprint, positioning engineering education to meet the global demand for graduates capable of integrated problem-solving and systemic thinking. This framework acts as the theoretical foundation for cultivating engineers who are not only technically proficient but also possess the intrinsic values (affective dimension) and actionable skills (behavioral dimension) necessary to navigate and solve complex global sustainability challenges.

ACKNOWLEDGEMENTS

The authors received no financial support for this work. The authors also wish to thank Mr Thevaraja Kumar (Introduction to Engineering) and Mr Soon Yew Boon (Design and Implement), for developing learning activities for their respective courses, to correspond with relevant sustainability mindset principles and UNSDGs. Special thanks to Dr Ngoh Shwu Lan for mapping out MAE's courses to relevant UNSDGs.

The GenAI tool ChatGPT was used to generate the "Double Helix DNA" diagram. Gemini was also used to provide suggestions for a more coherent conclusion, which was then written by the first author using his own words. The prompts used and responses obtained can be found in the **Link**.

REFERENCES

Alhassani, F., Saleem, M.R., & Messner, J. (2025). Integrating Sustainability in Engineering: A Global Review. *Sustainability*, 17(15), 6930. https://doi.org/10.3390/su17156930

Ayerbe, J., & Perales, F.J. (2024). Effects of a Project-based Learning Methodology on Environmental Awareness of Secondary School Students. *International Journal of Instruction*, 17(1), 1–22. https://www.e-iji.net/dosyalar/iji_2024_1_1.pdf

Azrai, E.P., Heryanti, E., Ramadhani, V., & Ilyas, M.S.Z. (2024). Enhancing Students' Pro-Environmental Behavior through Project-based Learning. *Biosfer: Jurnal Pendidikan Biologi*, 17(2), 317. https://doi.org/10.21009/biosferjpb.28352

Cheah, S.M., Lim, L.L., & Chao, Y.C. (2022). CDIO for Education for Sustainable Development using Common Core Curriculum. *Proceedings of the 18th International CDIO Conference*. Reykjavik, Iceland: Reykjavik University.

Cheah, S.M., Yang, K., Liow, Z., Wong, Y., Chia, C.L., & Wouterson, E. (2025). Using CDIO for Development of Students' Sustainability Mindset. *Proceedings of the 21st International CDIO Conference*. Melbourne, Australia: Monash University.

Deng, J., Du, L., Xia, J., Li, Y., & Cai, X. (2021). Eco-design Learning Framework on Integrating Life Cycle Assessment into Engineering Courses for Sustainability Competency Enhancement. *IEEE Access*, 9, 160596. https://doi.org/10.1109/access.2021.3132335

Guerra, A., Chen, J., Winther, M., Kolmos, A., & Nielsen, S.R. (2020). *Educate for the Future: PBL, Sustainability and Digitalisation 2020*. Technical University of Denmark. https://vbn.aau.dk/en/publications/educate-for-the-future-pbl-sustainability-and-digitalisation-2020/

Guerra, A., Ruge, G., & Ranito, J.J. (2023). *Who Am I and Why Am I Here? Academic Staff Viewpoints on CBL and Towards a Sustainability Mindset*. Technical University of Denmark. https://vbn.aau.dk/en/publications/who-am-i-and-why-am-i-here-academic-staff-viewpoints-on-cbl-and-t/

Kurkin, A., Kryukov, E., Маслеева, О.В., Petukhov, Y., & Гусев, Д. В. (2024). Comparative Life Cycle Assessment of Electric and Internal Combustion Engine Vehicles. *Energies*, 17(11), 2747. https://doi.org/10.3390/en17112747

Olsen, S.I., Nielsen, S.B., Ejlertsen, M.L., & McAloone, T.C. (2013). Teaching Sustainability in Engineering Solutions as a Generic Bachelor Course. Technical University of Denmark. https://orbit.dtu.dk/en/publications/teaching-sustainability-in-engineering-solutions-as-a-generic-bac/

Perpignan, C. (2021). Definition of Competencies Framework for Integration of Sustainable Engineering into Technological Curriculum: Application to Ecodesign. HAL. https://tel.archives-ouvertes.fr/tel-03692449

Rimanoczy, I. (2019). The 12 Sustainable Mindset Principles. https://isabelrimanoczy.net/wp-content/uploads/The-12-Sustainability-Mindset-Principles-presentation-nuevo.pdf

Sierra-Fontalvo, L., Gonza-Quiroga, A., & Mesa, J.A. (2023). A Deep Dive into Addressing Obsolescence in Product Design: A Review. *Heliyon*, 9(11).

United Nations. (n.d.). Sustainable development goals. https://sdgs.un.org/goals

United Nations Department of Economic and Social Affairs. (2025). *The Sustainable Development Goals Report 2025*. United Nations. https://doi.org/10.18356/9789211071597

BIOGRAPHICAL INFORMATION

Kim-Fai Soh is the Senior Manager for the Teaching and learning unit in the school of Mechanical and Aeronautical Engineering, Singapore Polytechnic. He is also the Program Chair for common engineering. His pedagogical interests include Authentic and Experiential Learning with deep industrial participation and Global Collaborative Learning.

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 Master Specialist (Teaching and Learning) in the School of Chemical and Life Sciences, Singapore Polytechnic. He has more than 18 years of experience implementing CDIO in the Diploma in Chemical Engineering curriculum and has conducted various CDIO workshops for universities in Asia, for various disciplinary programs. His academic interests include curriculum revamp, academic coaching and mentoring, and using GenAI in education.

Corresponding author –
Mechanical & Aeronautical Engineering

Kim-Fai Soh
Singapore Polytechnic School of
Mechanical & Aeronautical Engineering
500 Dover Road, Singapore 139651
SINGAPORE
Soh_Kim_Fai@sp.edu.sg

Corresponding author –
CDIO & Sustainable Development
Sin-Moh Cheah
Singapore Polytechnic Department
of Educational Development 500
Dover Road, Singapore 139651
SINGAPORE
Cheah_Sin_Moh@sp.edu.sg