MODEL PATHWAY IN CHEMICAL ENGINEERING TO DEVELOP STUDENTS' SUSTAINABILITY MINDSET USING CDIO

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ABSTRACT

This paper examines the evolving role of chemical engineering education in balancing process and product design to address sustainability challenges. Chemical engineering education has traditionally emphasized process design and operation, culminating in capstone plant design projects. In recent decades, however, chemical product design has emerged as an important complementary pathway, offering opportunities to address sustainability challenges more holistically. With the advent of the United Nations Sustainable Development Goals (UNSDGs), the discipline is increasingly being called upon to integrate sustainability principles into both process and product contexts. This paper builds on earlier work using the CDIO Framework to embed sustainability mindset development in chemical engineering curricula, extending the model to a "double helix" dual pathway of process and product design. The paper demonstrates how integrated learning experiences can be designed using GenAI and systematically structured to cultivate key competencies for sustainability. A revised set of eight competencies, aligned with the European GreenComp framework, is proposed to strengthen connections to sustainability mindset principles and address prior gaps such as problem framing. Systems thinking and values thinking are identified as the anchor competencies, one for each strand of the "double helix" pathway that intertwines analytical and ethical dimensions of sustainability learning. This pairing ensures that students not only grasp systemic complexity but also internalize fairness, responsibility, and personal agency. This paper shares a possible double helix for chemical engineering, with integrated learning experiences that progressively expose students to sustainability issues of increasing complexity, supported by faculty oversight. The approach is equally applicable to programs with only process pathways or beyond chemical engineering, offering a reproducible model for embedding sustainability mindset across disciplines. Lastly, the paper discusses the advantages and limitations of the double helix model, and the need to continue keeping abreast with technological development given the dynamic nature of sustainable development.

KEYWORDS

Sustainability Mindset, Chemical Engineering, Key Competencies for Sustainability, Double Helix, CDIO Standards 1, 2, 3 and 7

INTRODUCTION

The discipline of chemical engineering often focused on the teaching of chemical process design and operation, culminate in the final year plant design project where students working in teams using professional simulation software, produced a design “package” of a chemical processing plant to produce a given chemical product of desired specifications, complete with a blueprint of how the plant is to be constructed. This had been the dominant approach for all chemical engineering programs. On the other hand, starting in the late 1990s to early 2000s, the coverage of chemical product design and development started to appear in some chemical engineering programs, see for example Moggridge & Cussler (2000). This is followed by the publication of the textbook *Chemical Product Design* by these 2 authors, widely considered as the first dedicated contribution to the teaching of the subject (Cussler & Moggridge, 2001).

With the introduction of United Nations Sustainable Development Goals (UNSDGs), education had become a key approach to addressing sustainability issues. Chemical engineering programs are no exception, and the teaching of chemical engineering principles has been enhanced to include contribution of the discipline towards sustainable development. Traditional programs that focused on chemical process design and operation have begun introducing chemical product design and development into the curriculum. The chemical engineering program from Singapore Polytechnic (SP) is one such program that used the CDIO Framework to redesign its traditional curriculum to offer both process and product learning pathways to its students (Cheah, 2021). Further work on integration of sustainable development in SP centered on using the CDIO Framework to develop sustainability mindset for students and the effort is still on-going (Cheah *et al*, 2025; Yang & Cheah, 2025).

Scope of This Paper

This paper continues the previous effort, leveraging on new developments in the use of generative artificial intelligence (GenAI) in tandem with the CDIO Framework reported by Cheah (2026a). More specifically, this paper strives to demonstrate how the model of progressive learning pathway by Cheah *et al* (2025) can be designed for a chemical engineering program with both process design and product design learning pathways. The author further argues that such dual pathway chemical engineering programs are uniquely posed to offer a more integrated approach toward addressing sustainability challenges.

This paper also contributes to the ongoing discourse in the chemical engineering community on the teaching of chemical product design, which had been slow to permeate into the traditionally process-oriented nature of chemical engineering education. This paper will briefly discuss the challenges faced in driving chemical product design forward, despite the acknowledge benefits it delivers. It will also improve on the model by Cheah *et al* (2025) by incorporating new developments in key competencies for sustainability and strengthen the connection to sustainability mindset principles. The approach shared will add to the repertoire of tools progressive developed for chemical product design and development, focusing on active and experiential learning in implementing sustainability initiatives to develop students’ sustainability mindset.

However, it must be stressed that the approach outlined in this paper is equally applicable to chemical engineering programs with only process design pathway, and for that matter any program beyond chemical engineering. However, the choice of the dual pathway is meant to illustrate the mutually supporting and complementary nature of the 2 pathways which augurs well with the intent of the integrated curriculum design of CDIO.

CHEMICAL PROCESS VS PRODUCT DESIGN: SUSTAINABILITY CHALLENGES

In chemical engineering education, both pathways share core principles unique to chemical engineering such as mass and energy balances, chemical thermodynamics, reaction kinetics and transport phenomena. Henceforth the same principles are used in both pathways, although the learning objectives are different for each pathway. Chemical process design focuses on *how* to make something efficiently (focusing on topics such as unit operations, thermodynamics, simulation, safety, scale-up), while chemical product design focuses on *what* to make (focusing on formulations, material properties, functionality for end-use, market needs). Process design optimizes existing or new production lines (distillation, reactors), whereas product design creates novel materials or formulations for specific applications (pharmaceuticals, specialty chemicals, personal care).

Chemical process design and operations differ significantly from chemical product design and development when it comes to sustainability issues, with divergence both in scope and impact. These can be summarized in Table 1 below.

Table 1. Key sustainability challenges for chemical process vs product design

Chemical Process Design & Operations	Chemical Product Design & Development
• Energy intensity & emissions: Chemical plants contribute significantly to global CO_2 emissions; decarbonizing energy use is critical • Feedstock variability: Transitioning from fossil-based to renewable feedstocks (biomass, waste streams) introduces variability in quality and supply • Waste minimization: Designing closed-loop systems to reduce hazardous by-products and effluents • Safety & resilience: Balancing sustainability with operational safety, especially under uncertain supply chains • Integration with circular economy: Processes must adapt to recycling and revalorization of materials	• Life-cycle impacts: Products must be designed with cradle-to-grave considerations - minimizing hazards, emissions, and waste across their entire lifespan • Material innovation: Developing safer, biodegradable, or recyclable chemicals and polymers • Consumer & regulatory pressures: Sustainability is now a market differentiator, but aligning innovation with evolving regulations is complex • Green chemistry principles: Embedding atom economy, safer solvents, and reduced toxicity into product design • Scalability & adoption: Sustainable products often face barriers in scaling economically while competing with entrenched conventional products

Despite their inherent differences, a compelling case exists for integrating these two pathways to cultivate a robust sustainability mindset in students. Regarding chemical process design and operation, students must look beyond mere efficiency to prioritize systemic resilience, adaptability, and long-term environmental health. This shift demands a high tolerance for ambiguity, the ability to navigate complex socio-economic trade-offs, and the courage to challenge conventional economic models. Regarding chemical product design and development, students must embrace a deeper sense of responsibility – anticipating unintended consequences and championing ethical innovation through life-cycle stewardship. Integrated, these pathways empower chemical engineers to safeguard ecological systems while driving meaningful economic and societal progress.

Coverage of Chemical Product Design in Chemical Engineering Curriculum

This author conducted a “quick-and-dirty” survey to ascertain the number of chemical engineering programs worldwide that offer chemical product design in the curriculum. This is just to obtain a sense of the extent of adoption of chemical product design to-date. Therefore, an exact percentage of undergraduate chemical engineering programs with elements of chemical product design is not necessary. The methodology is straight-forward. The author first obtained the name of universities offering chemical engineering programs from the Times Higher Education (THE) World University Ranking. The list is fed into Google Gemini with prompts requesting it to visit the website of each university and report on the chemical engineering program offered, and where chemical product design is present; and if present to indicate with short explanatory notes whether the coverage of chemical product design is explicitly mentioned or inferred. Due to the sheer number of universities, only the top 259 was analyzed. Results with inferred presence of chemical products were eliminated via manual check by the author, as the inference was made based on subjects offered, which may be related to product design. The final result showed that the distribution is almost equal: 47.5% of universities offer chemical product design, i.e. explicitly mentioned in its website.

Challenges in Integrating Chemical Product Design

In October 2023, Computer Aids for Chemical Engineering (CACHE), a non-profit organization dedicated to developing and distributing technology-based educational materials and software for the profession, commissioned a Design Task Force dedicated to conducting a year-long review of chemical product design education worldwide. It delivered a disappointing finding that the integration of chemical product design remained limited (Seider *et al*, 2025). Most programs are still dominated by chemical process design, with chemical product remaining at the peripheral.

The challenges hampering progress include the following (Seider *et al*, 2025; Fung & Ng, 2018; Rodrigues & Cussler, 2016; Seider & Widogdo, 2012; Skov & Kiil, 2011):

1. *Lack of standardization*: No consensus on what and how to teach chemical product design resulting in teaching approaches vary widely across institutions. There is also no “standard” software compared to chemical process design.
2. *“Beyond engineering”*: Teaching chemical product design requires interdisciplinary thinking, and competency in various “soft” skill such as creativity, customer needs, market demand.
3. *Lack of teaching resources*: There is no agreed model for teaching, resulting in varying approaches across institutions. Lack of understanding on how product formulation and/or processing conditions lead to final product performance is also another concern.
4. *Use of specialized technologies*: Chemical products often rely on equipment and unit operations not usually covered in core curriculum.
5. *Faculty discomfort*: More ambiguity and uncertainty over the outcomes, coupled with the higher workload perceived for handling product design which is more open-ended in nature.
6. *Industry support*: Collaborations between academia and industry exist but are not widespread; with many programs lack strong industry ties for experiential learning, e.g. due to faculty lacking relevant real-world experience to form partnership with industry.
7. *Sustainability*: This will add another dimension to the teaching of chemical product design, adding to the challenges identified above, e.g. dealing with empathy, values and beliefs, lifecycle analysis, carbon footprint, etc.

SP-CDIO MODEL FOR INTEGRATING KEY COMPETENCIES FOR SUSTAINABILITY & COVERAGE OF SUSTAINABLE DEVELOPMENT IN SP-CDIO SYLLABUS: AN UPDATE

Cheah *et al* (2025) had shared an approach to developing students' sustainability mindset using the CDIO Framework, which is useful for adoption by any programs. It is derived from an extensive review of extant literature on what constituted the key competencies for sustainability that are needed to carry out sustainability initiatives. The approach predicates on a set of 12 sustainability mindset principles (Rimanoczy & Llamazares, 2021) that can be developed alongside the application of key competencies for sustainability, leading to the development of sustainability mindset (Kassel, Rimanoczy & Mitchell, 2016).

One key omission from the works of Cheah *et al* (2025) is the inclusion of the European framework for sustainability competence called the GreenComp (Bianchi *et al*, 2022). GreenComp suggests 4 areas with 3 competences each: (1) *Embodying Sustainability Values*, (2) *Embracing Complexity in Sustainability*, (3) *Envisioning Sustainable Futures*, and (4) *Acting for Sustainability*. A quick analysis of the underpinning skills and attitudes for the 12 competences (not elaborated in this work) showed close matching to the 8 key competencies for sustainability from Cheah *et al* (2025) except for "Problem Framing". This is a key distinction from GreenComp and an important one – it explicitly brings out attributes such as fairness and adaptability; and directly address the drivers for "bias for action" in tackling sustainability issues via individual initiative, collective action and political agency. Hence, for this work, this author proposed that it be subsumed into Integrated Problem-Solving Competency, and the GreenComp "Problem Framing" added, to be termed Problem Framing Competency as enhancement of the earlier model by Cheah *et al* (2025).

Furthermore, the inclusion of Implementation Competency into the key competencies has been debatable (Cheah *et al*, 2025). This, plus the desire to avoid creating of a laundry list of key competencies for sustainability, this work proposes that Implementation Competency be subsumed under Integrated Problem-Solving Competency, thus maintaining the number of key competencies for sustainability at 8. The descriptors for the revised set of 8 key competencies for sustainability were reworded for better alignment for the 4 competences areas of GreenComp. The result is shown in Table 2.

The revised key competencies for sustainability along with another strand of work by the author to revise the existing SP-CDIO Syllabus, also lend themselves more readily to better alignment with the 12 sustainability mindset principles which was grouped into 4 areas: (1) *Ecological Worldview* with 2 principles of "Ecoliteracy" and "My Contribution"; (2) *Systems Perspective* with 4 principles of "Long-term Thinking", "Flow in Cycles", "Both+And Thinking" and "Interconnectedness"; (3) *Spiritual Intelligence* with 3 principles of "Purpose", "Oneness with Nature" and "Mindfulness"; and (4) *Emotional Intelligence* with 3 principles of "Creative Innovation", "Reflection" and "Self-awareness".

Detailed discussions of the suggested revisions to the CDIO Syllabus version 3.0 have been detailed elsewhere (Cheah, 2026c). Suffice to note here that earlier work by Cheah *et al* (2025) had noted the "not-too-ideal" mapping between the CDIO Syllabus with the 12 sustainability mindset principles. One key aspect of the suggested revisions is to include more "inner dimensions" of skills and attitudes desired in students. This would improve the mapping between the revised and updated CDIO Syllabus and the 12 sustainability mindset principles. Table 3 shows the updated mapping with the addition of Problem Framing Competency and the absorption of Implementation Competency into Integrated Problem-Solving Competency.

Table 2. Alignment of 8 key competencies for sustainability to GreenComp competence

#	Key Competency	Descriptor (updated with GreenComp input)	Alignment to GreenComp
1	Values Thinking	Ability to anchor decisions in ethical principles, fairness, and responsibility, ensuring sustainability choices reflect human and ecological integrity.	*Embodying sustainability values:* 1.1 Valuing Sustainability 1.2 Supporting Fairness
2	Intrapersonal Competency	Ability to cultivate self-awareness, resilience, and mindfulness to manage ambiguity, align personal values, and sustain motivation in complex contexts.	*Envisioning sustainable futures:* 3.2 Adaptability 1.3 Promoting Nature
3	Interpersonal Competency	Ability to collaborate across diverse stakeholders, communicate effectively, and build trust for collective sustainability action.	*Acting for sustainability*: 4.1 Political Agency 4.2 Collective Action
4	Systems Thinking	Ability to analyze interconnections within natural, social, and technical systems, recognizing feedback loops, trade-offs, and unintended consequences.	*Embracing complexity in sustainability:* 2.1 Systems Thinking
5	Futures Thinking	Ability to anticipate long-term scenarios, envision alternative futures, and design resilient strategies under uncertainty.	*Envisioning sustainable futures:* 3.1 Futures Literacy 3.3 Exploratory Thinking
6	Problem Framing Competency (new)	Ability to define and structure sustainability challenges, clarify boundaries, and reframe issues to reveal opportunities for innovative and responsible solutions.	*Embracing complexity in sustainability:* 2.3 Problem Framing
7	Strategic Thinking	Ability to identify leverage points, prioritize interventions, and design phased pathways for systemic change.	*Embracing complexity in sustainability:* 2.2 Critical Thinking 2.3 Problem Framing
8	Integrated Problem-Solving Competency (merged with Implementation)	Ability to synthesize diverse knowledge and perspectives into coherent solutions, and to design actionable pathways for adoption, piloting, and scaling.	*Acting for sustainability:* 4.3 Individual Initiative

DEVELOPING SUSTAINABILITY MINDSET FOR CHEMICAL ENGINEERING STUDENTS

Systems thinking is the most important consideration in traditional chemical engineering program – which as we had seen earlier, is solidly grounded in chemical process design and operation. It provides a holistic perspective that considers the complex interactions and interdependencies among all process components in a chemical plant, ensuring greater safety, efficiency, and sustainability. It helps engineers anticipate unintended consequences that arise when optimizing only isolated parts of the plant. A particular type of systems thinking is lifecycle thinking which underpins the concept of circular economy, an important framework in promoting net zero emission practices throughout the lifecycle of a product (Heard & Vaccari, 2024). Hence using systems thinking competency to serve as the “spine” to progressively develop students’ sustainability mindset over the program duration is the most appropriate choice. This can be done via a series of CDIO integrated learning experiences (Standard 7) using suitable UNSDGs as the learning contexts, supported by other key competencies for sustainability (Cheah *et al*, 2025). When used in chemical product design and development, it can aid in identifying possible unintended consequences by surfacing interactions between elements that are not immediately obvious.

Table 3. Mapping between revised key competencies for sustainability with sustainability mindset principles

Sustainability Mindset Principles		Values Thinking	Intrapersonal	Interpersonal	Systems Thinking	Futures Thinking	Problem Framing	Strategic Thinking	Integrated Problem-Solving
Ecological Worldview	Ecoliteracy				X		X		
	My Contribution	X	X	X					
Systems Perspective	Long-term Thinking				X	X	X	X	
	Flow in Cycles				X		X		
	Both+And Thinking			X	X		X	X	X
	Interconnectedness	X		X	X	X	X	X	X
Spiritual Intelligence	Purpose	X	X	X		X		X	X
	Oneness with Nature	X							
	Mindfulness	X	X		X		X		X
Emotional Intelligence	Creative Innovation		X					X	X
	Reflection	X	X	X	X	X	X	X	X
	Self-awareness	X	X				X		X

Furthermore, sustainable development is inherently a value-laden topic. Sustainability challenges are inherently normative and contested, requiring students to navigate trade-offs, justice, and long-term ethics. This is because sustainability is not merely a technical or scientific issue but one fundamentally intertwined with ethics, morality, and subjective societal beliefs. Decisions regarding sustainability often involve balancing competing priorities and differing worldviews about what constitutes a desirable and just future. Given the cognitively heavy demand of systems thinking, it may over-emphasize analytical reasoning at the expense of emotional, spiritual, and values-based dimensions of sustainability mindset. Students may grasp systems logic but not internalizing personal agency or values that are essential for transformative impact towards sustainable development: “Head without heart”. There is a risk of “intellectualization of sustainability” where students understand complexity of the challenges but remain emotionally detached. This will undermine the much-needed mindset change. Transformative learning requires emotional engagement, introspection, and ethical reflection – dimensions not inherently activated by systems logic. These aspects of transformation are best developed using values thinking competency. In the absence of value-based considerations, systems models may focus solely on efficiency, potentially overlooking important factors such as equity and ecological integrity.

Hence, it would be logical to “pair” systems thinking competency with values thinking competency, creating what the author call a “double helix” (a term borrowed from the life sciences describing the structure of a DNA molecule where the 2 strands wound around each other, carrying the genetic instructions for all living organisms) development pathway for sustainable mindset development of students from for chemical engineering programs focusing on both chemical processes and products. Such an approach offers greater opportunities for tackling different aspects of sustainability issues. One “strand of the DNA” would be the systems thinking competency, and the “other DNA strand” would be the values thinking competency.

A hypothetical example is shown in Figure 1, where a series of CDIO integrated learning experiences is designed using systems thinking competency and values thinking competency as “key anchors” onto which students working in teams address sustainability issues of increasing complexity from simple to complicated to complex.

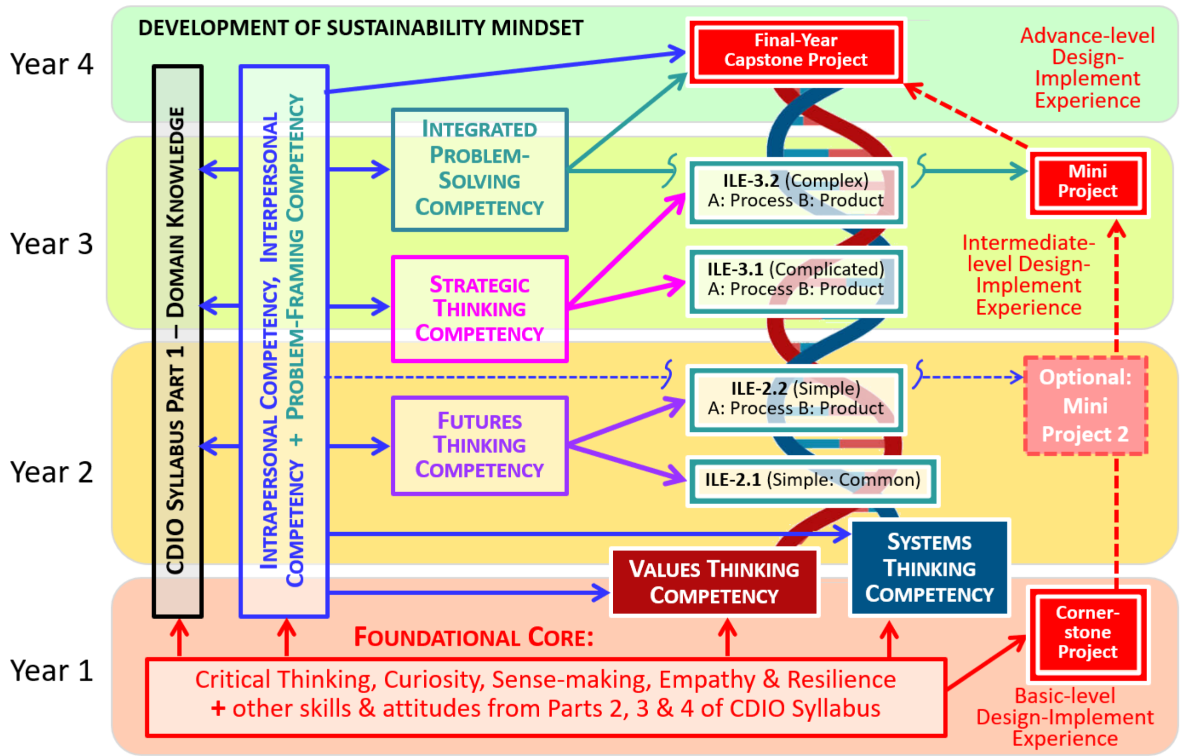

Figure 1. Proposed double helix development pathway for developing sustainability mindset

Integrated learning experiences are preferred over design-implement experiences for the systematic development of sustainability mindset. This is because integrated learning experiences offer a most systematic and “controlled” way to structure the learning experiences such that all students are exposed to the challenges in the same manner, to the desired level of proficiency. This contrasts with the use of projects in design-implement experiences where there are more variations from project to project, such that it is more challenging to mandate the same affective-type learning outcomes from different projects.

As can be seen in Figure 1, there are altogether 7 integrated learning experiences denoted by the acronym ILE-X.X. As an example, ILE-2.1 denotes integrated learning experience for Year 2 Semester 1, which is the very first learning task for students, with simple sustainability issues to be addressed.

This model shows that Year 1 is used to introduce students to the fundamental skills and attitudes needed to develop key competencies for sustainability. We suggest that the learning context for ILE-2.1 to be based on sustainability issues that are familiar to students to illustrate how the systems thinking competency and values thinking competency mutually support one another. Subsequent ILEs beginning with Year 2 Semester 2 (i.e. ILE-2.2) will feature learning contexts aligned to the 2 learning pathways: “A” for chemical process design and operation, and “B” for chemical product design and development.

Futures thinking competency is introduced in Year 2 to “prime” students to envision a more sustainable future, while strategic thinking competency is introduced in Year 3 to start exposing students to the need to plan for engaging key stakeholders in launching their proposed sustainability initiative. Students will be required to demonstrate the various key competencies for sustainability in their respective final year capstone projects.

The pedagogical logic for the 3 integrated learning experiences for increasing challenge in addressing sustainability issues can be summarized as follows:

- ILE-2.1: Familiar, everyday sustainability issue to build awareness and invoke a sense of personal responsibility
- ILE-2.2: Discipline-specific but simple sustainability issues to introduce technical grounding in process and product contexts
- ILE-3.1: Complicated industrial issues, with the need to address various trade-offs and resolve contested values while maintaining the required technical rigor
- ILE-3.2: Complex systemic redesign to tackle wicked problems requiring integration of systems thinking and values thinking

Design of Integrated Learning Experiences for Sustainable Development

Among the many aspects that GenAI can assist faculty in matters related to teaching and learning, of interest in this paper is the design of integrated learning experiences to develop the key competencies for sustainability as envisioned in Figure 1. Cheah (2025b) had shared how faculty can use GenAI guided by CDIO Standards to carry out curriculum design, highlighting aspect of the effort that required human oversight (human-in-the-loop) to guard against limitations of GenAI. Table 4 summarizes key considerations of relevant CDIO standards related to using GenAI to aid the design of the development pathways.

Table 4. Use of GenAI and faculty oversight for related CDIO standards

CDIO Standard	Use of GenAI	Faculty Oversight (Human-in-the-Loop)
1 – The Context	Identify appropriate UNSDGs relevant to the program and scenarios used (see Standard 7)	Each scenario is of appropriate level of difficulty, progression is acceptable Context is appropriate for year of study
2 – Learning Outcomes	Suggest skills and attitudes needed Suggest possible learning outcomes	Ensure underpinning skills and attitudes, e.g. teamwork, communication, critical thinking, etc are already adequately developed in earlier courses, although the contexts may be different
3 – Integrated Curriculum	NOT USED	Decide on which courses are most appropriate for each scenario Identify available supporting courses with needed prior knowledge
6 – Engineering Learning Workspaces	NOT USED	Identify adequacy of existing facilities and environment to support learning context and desired learning outcomes
7 – Integrated Learning Experiences	Generate task scenarios for different levels of difficulty: Simple Complicated and Complex; suggest plausible unintended consequences for each scenario	Ensure suitable scaffolding are provided at each level and matched to the level of difficulty
11 – Learning Assessment	Suggest questions for in-class assessment, debrief, and report writing Prepare performance rubric	Review questions posed for relevance and validity Check reasonableness of rubrics Ensure that skills and attitudes are assessed in context and constructive alignment is maintained
12 – Program Evaluation	Suggest potential areas that require faculty oversight	Look into one’s own experience to ascertain any other aspects that GenAI may have missed

As argued in earlier section of this paper, adding the considerations from GreenComp to the key competencies for sustainability had strengthened the connections with sustainability mindset principles. With the design of the 7 ILEs using GenAI we can have an implementable approach that build on the theoretical considerations of Cheah *et al* (2025) towards developing students' sustainability mindset. Effectively they serve 2 purposes: first is to develop the necessary sustainable mindset principles in students, appropriate to the context of the task-at-hand; and secondly to link the principles to key competencies for sustainability that are to be used in tackling the sustainability issue. Table 5 shows the different sustainability issues as suggested by GenAI for the integrated learning experiences, and the main sustainability mindset principles activated.

Table 5. Sustainability mindset principles activated in each integrated learning experience

Year & Level	Sustainability Issue	Main Sustainability Mindset Principles Activated
Year 2.1 Simple: Common	Reducing single-use plastics in campus cafeterias	**Ecoliteracy** (understanding plastic impacts) **My Contribution** (personal agency, footprint reduction) **Interconnectedness** (linking campus choices to global pollution) **Flow in Cycles** (materials must circulate) **Reflection** (journaling on convenience vs. consequence)
Year 2.2 Simple: A. Process	Reducing energy waste in laboratory-scale distillation units	**Ecoliteracy** (energy flows, emissions) **Interconnectedness** (lab choices → campus energy budgets) **Both+And Thinking** (efficiency + safety) **Long-term Thinking** (sustaining improvements across cohorts) **Mindfulness** (attentiveness to operational discipline) **Reflection** (learning from iterative improvements)
Year 2.2 Simple: B. Product	Formulating eco-friendly cleaning products for campus use	**Ecoliteracy** (toxicity, biodegradability) **Interconnectedness** (users, wastewater systems) **Creative Innovation** (new formulations) **Both+And Thinking** (performance + ecological safety) **Purpose** (aligning with stewardship and health) **Reflection / Self-awareness** (challenging assumptions about "clean")
Year 3.1 Complicated: A. Process	Optimizing water & energy use in a mid-scale chemical plant	**Interconnectedness** (water–energy–emissions links) **Long-term Thinking** (resource stress scenarios) **Both+And Thinking (**quality + efficiency) **Flow in Cycles** (reuse/recovery loops) **Purpose** (aligning plant goals with community) **Reflection / Self-awareness** (bias checks in optimization)
Year 3.1 Complicated: B. Product	Developing safer solvents for industrial and consumer applications	**Ecoliteracy** (hazards, exposure routes) **Long-term Thinking** (regulatory foresight) **Interconnectedness** (supply chain mapping) **Creative Innovation** (ionic liquids, CO_2 solvents) **Both+And Thinking** (performance + safety + cost) **Self-awareness** (worker/consumer perceptions)
Year 3.2 Complex: A. Process	Designing a circular economy strategy for chemical processes	**Interconnectedness** (multi-party flows) **Flow in Cycles** (closed-loop systems) **Long-term Thinking** (multi-decade scenarios) **Both+And Thinking** (economic + ecological goals) **Purpose** (stewardship charter) **Mindfulness / Reflection** (deliberation under uncertainty)
Year 3.2 Complex: B. Product	Designing circular economy strategies for chemical products (e.g. polymers, pharmaceuticals	**Ecoliteracy** (polymer recyclability, toxicity) **Interconnectedness** (value chain mapping) **Flow in Cycles** (design for disassembly, passports) **Long-term Thinking** (future infrastructure, standards) **Creative Innovation** (safe-by-design prototypes) **Both+And Thinking** (durability + recyclability) **Purpose / Mindfulness / Reflection** (ethical navigation of trade-offs)

Each of the integrated learning experiences will require students to use systems thinking to identify the potential trade-off and plausible unintended consequences that may arise from each proposed solution. These activities will also provide students with ample opportunities to discuss the relative merits of each situation not only from the technical requirements and feasibility, but more importantly from socio-economic and cultural perspectives – i.e. applying values thinking – to develop a more holistic understanding of the sustainability issue on hand. Table 6 shows summarize the trade-offs and unintended consequences as suggested by GenAI for each integrated learning experience. Faculty interpretations of the suggestions using one's domain expertise are necessary to provide the required human-in-the-loop scrutiny of GenAI outputs to ensure relevance.

Table 6 also shows examples of how other key competencies, namely interpersonal, intrapersonal, futures thinking and strategic thinking can support the double helix competencies of systems thinking and values thinking. Table A1 in the Appendix provides examples of other skills and attitudes required to develop these required key competencies for sustainability. Note that the list shown is not exhaustive and that actual "sequence" of their integration must necessarily follow specific program's own approach in developing the key competencies for sustainability. Note also that specific courses where such skills and attitudes are to be included are also deliberately omitted. The flexible approach afforded by this model is meant for any program to leverage on its own curriculum structure to progressively build up students' sustainability mindset in using the appropriate UNSDGs as learning contexts.

Lastly, Table 7 shows the performance indicators for each of the integrated learning experiences produced by GenAI, based on the specific task scenarios. GenAI can help to further develop them into performance rubrics, for example using the Dreyfus Scale. Once again, human oversight is necessary to ensure the proper use of GenAI.

DISCUSSIONS: ADVANTAGES AND LIMITATIONS OF DOUBLE HELIX APPROACH

The double helix approach towards sustainability mindset development can potentially provide a more structured approach to tackling wicked sustainability issues, by emphasizing both "head and heart" to work in tandem: systems thinking ensuring that students can analyse complex interdependencies, optimize processes, and anticipate unintended consequences; while values thinking anchors those analyses in ethics, fairness, and ecological responsibility, preventing purely efficiency-driven solutions. Ethical reflection guides students in navigating the trade-offs and can potentially inspire more innovative system redesigns that might not emerge from technical analysis alone.

One aspect that flows naturally that needs to be addressed in the future is that of convergence between chemical process design and chemical product design, which further extend the development of sustainability mindset towards a holistic encapsulation. Much work needs to be done in this area. Fung & Ng (2018) for example presented a comprehensive approach that integrates product design with process design. It begins with a market study to gather market information, compare competing products, identify qualitative product attributes for satisfying consumer preferences which are then converted to quantitative technical parameters through heuristics, mathematical models, experiments, tools, and databases. A suitable manufacturing process is then synthesized to produce the product with the required product specifications, followed by a financial analysis to evaluate product profitability. Two case studies were shared. The author hope that the double helix approach presented in this paper can contribute positively to this endeavour.

Table 6. Summary of integrated learning experiences designed by Gemini

Year & Level	Sustainability Issue	Main SDGs	Key Trade-off	Unintended Consequences	"Double Helix" Competency	Other Supporting Competencies (not including Integrated Problem-Solving)
Year 2.1 Simple: Common	Reducing single-use plastics in campus cafeterias	12, 13, 14	Convenience & cost vs. ecological responsibility	1. Higher water/energy use for washing reusables 2. Hygiene risks if cleaning inadequate 3. Resistance due to inconvenience	Systems thinking (material flows, waste loops) Values thinking (responsibility, fairness)	Intrapersonal (personal responsibility, habit change) Interpersonal (peer influence, collective action)
Year 2.2 Simple: A. Process	Reducing energy waste in laboratory-scale distillation units	7, 12, 13	Efficiency gains vs. upfront modifications	1. Added complexity in lab operations 2. Potential safety risks if insulation poorly applied 3. Increased maintenance burden	Systems thinking (energy flows) Values thinking (resource stewardship)	Strategic Thinking (targeting low-hanging efficiency gains) Intrapersonal (attention to detail, stewardship mindset)
Year 2.2 Simple: B. Product	Formulating eco-friendly cleaning products for campus use	3, 6, 12	Performance & cost vs. ecological safety	1. Reduced cleaning effectiveness 2. Higher costs for biodegradable ingredients 3. Wastewater treatment challenges from new formulations	Systems thinking (life cycle of products) Values thinking (health, ecological safety)	Interpersonal (user safety, stakeholder empathy) Strategic Thinking (balancing performance vs. safety)
Year 3.1 Complicated: A. Process	Optimizing water and energy use in a mid-scale chemical plant	6, 7, 9, 12	Operational efficiency vs. capital investment	1. Water reuse concentrates contaminants 2. Reduced cooling may affect product quality 3. Increased emissions from added treatment chemicals	Systems thinking (resource interdependencies) Values thinking (equity in resource use)	Strategic Thinking (multi-variable trade-offs) Futures Thinking (long-term resource resilience) Intrapersonal (resilience under constraints)
Year 3.1 Complicated: B. Product	Developing safer solvents for industrial and consumer applications	3, 9, 12, 13	Safety & sustainability vs. performance & cost	1. Bio-based solvents compete with food crops 2. New infrastructure/disposal needs 3. Market resistance if performance drops or costs rise	Systems thinking (life cycle, substitution impacts) Values thinking (health, justice, responsibility)	Futures Thinking (anticipating regulatory shifts) Interpersonal (collaboration across supply chain) Strategic Thinking (designing for adoption)
Year 3.2 Complex: A. Process	Designing a circular economy strategy for chemical processes	7, 9, 12, 13, 17	System redesign vs. economic competitive-ness	1. Impurity accumulation in recycling loops 2. Increased operational complexity & safety risks 3. Higher global energy demand despite local waste reduction	Systems thinking (closed loops, cross-sector integration) Values thinking (long-term stewardship, fairness)	Futures Thinking (scenario planning, long-term loops) Strategic Thinking (leveraging systemic interventions) Interpersonal (cross-sector collaboration)
Year 3.2 Complex: B. Product	Designing circular economy strategies for chemical products (e.g. polymers, pharmaceuticals)	3, 9, 11, 12, 17	Innovation & sustainability vs. scalability & affordability	1. Lack of recycling infrastructure 2. Regulatory delays for safe-by-design products 3. Consumer scepticism/ greenwashing concerns	Systems thinking (cradle-to-grave product flows) Values thinking (safe-by-design, justice, transparency)	Futures Thinking (designing for future infrastructure) Interpersonal (engaging consumers, regulators) Intrapersonal (ambiguity tolerance, ethical creativity)

Table 7. Performance indicators for integrated learning experiences

Year & Level	Pathway	Sustainability Issue	Performance Indicators
Year 2.1 (Simple)	General	Reducing single-use plastics in campus cafeterias	Identifies material flows of plastics and alternatives (systems thinking) Articulates ethical trade-offs between convenience and ecological responsibility (values thinking) Demonstrates reflection through journaling or discussion Proposes feasible campus-level interventions with cost-benefit awareness.
Year 2.2 (Simple)	Process	Reducing energy waste in lab-scale distillation units	Calculates energy balances and quantifies efficiency improvements Applies safety checks when modifying lab setups Explains stewardship values in resource use Documents unintended consequences (e.g. maintenance burden) in lab reports.
Year 2.2 (Simple)	Product	Formulating eco-friendly cleaning products	Designs and tests formulations with measurable biodegradability/toxicity outcomes Balances performance vs. ecological safety in product evaluation Reflects on consumer perceptions of “clean” in written reports Demonstrates creative innovation in proposing alternatives
Year 3.1 (Complicated)	Process	Optimizing water & energy use in mid-scale plant	Builds simulation models showing water-energy-emission interdependencies Identifies trade-offs between operational efficiency and capital investment Justifies decisions using fairness in resource allocation Communicates optimization results with stakeholder-oriented clarity
Year 3.1 (Complicated)	Product	Developing safer solvents	Compares solvent properties (toxicity, performance, cost) using quantitative metrics Anticipates regulatory and market adoption challenges Applies substitution analysis (life-cycle impacts) Reflects on justice and responsibility in solvent design choices
Year 3.2 (Complex)	Process	Designing circular economy strategies for chemical processes	Maps closed-loop flow across multiple sectors Identifies impurity accumulation and safety risks in recycling loops Proposes phased redesign strategies balancing competitiveness and stewardship Demonstrates long-term thinking in scenario planning
Year 3.2 (Complex)	Product	Designing circular economy strategies for chemical products	Conducts cradle-to-grave analysis of product flows Designs safe-by-design prototypes with measurable recyclability Anticipates unintended consequences (e.g. infrastructure gaps, consumer skepticism) Demonstrates transparency and justice in trade-off communication.

At the time of this writing, the SP chemical engineering program is undergoing curriculum revamp to adopt the SP-CDIO model of integrating key competencies for sustainability to develop the sustainability mindset of its students. Given the complexity of the program, it may pilot with only systems thinking as a “single DNA strand” as a staged approach focusing first on the process design and operation pathway. Details of work done can be expected at future conference. Another program from SP, that for mechanical engineering, will be piloting using the double-helix model, but using Integrated Problem-Solving Competency and Systems Thinking Competency as the 2 drivers for sustainability mindset development. Details of this work is covered elsewhere (see Soh & Cheah, 2026).

Until then, there ideas and approaches presented in this paper is still grounded in theoretical considerations. Pilot running to operationalize the model has been initiated, and earlier programs in SP that uses the first version of the model (Chia & Cheah, 2025; Liow & Cheah, 2025) can provide valuable insights that can improve on the model and may adopt the double-helix enhancement in the respective program's later iteration.

However, there are potential downsides to the double helix approach, for example, when one over-emphasize either systems thinking or values thinking. If systems thinking dominates, students may end up focusing on models, efficiency, and optimization while neglecting values, empathy, and justice. On the other hand, if values thinking dominates, students may become idealistic without sufficient technical grounding, leading to solutions that are ethically sound but impractical or unscalable. The approach may make the teaching of sustainable development even more challenging for faculty, as they perceived the need to grapple with more topics that are beyond what they were comfortable with – especially those dealing with values, empathy, beliefs and fairness. Assessments can be particularly problematic. Traditionally systems thinking outcomes such as process simulations, efficiency metrics are easier to measure. On the other hand, values thinking outcomes are more subjective and harder to evaluate consistently. Faculty may struggle to design rubrics that capture learning outcomes for the affective domain without reducing them to superficial checklists.

DISCUSSIONS: USE OF GEN AI, AND MOVING AHEAD

With the advent of GenAI, the experience from this author in using it to design integrated experiences for this paper had demonstrated that the effort can be accomplished in much shorter time than doing them manually. The massive capability of GenAI can helped to assemble the whole suite of workplace scenarios, mapping to relevant UNSDGs, suggest student activities along with task-specific performance rubrics. With skilful crafting of the prompts and closely scrutinizing the outputs produced by GenAI, faculty can exercise responsible use of the tool required by human-in-the-loop to maintain oversight (see Table 4). Comprehensive faculty professional development in GenAI for example using the United Nations Educational, Scientific and Cultural Organization (UNESCO) AI Competency Framework for Teachers will be useful (Cheah, 2026d). More importantly, the outputs produced by GenAI, notably those related to the use of domain knowledge need to be reviewed by the subject matter expert(s) especially on the various scenarios, and the corresponding key trade-off and unintended consequences (Table 6) as well as the performance indicators (Table 7) to ascertain their suitability for in the real-world context for developing the required key competencies for sustainability (Table 5) and sustainability mindset principles (Table 6).

One area that warrants further research is the possible influence that values or beliefs has on problem framing competency that we added to the model. Values and beliefs can function as a filter and/or a lens through which individuals interpret information, giving meaning to situations and determining which aspects of a problem are considered important. This process significantly shapes how a problem is framed, influencing the definition of the issue, the potential solutions considered, and the willingness to cooperate with others.

Lastly, we need to remember that the challenge of sustainable development is a dynamic one because the nature, scope, and solutions related to sustainability are constantly evolving. Sustainability is not a single issue but a complex web of interconnected challenges. This dynamism is driven by several factors, for example new scientific understanding such as complex feedback loops of climate change, technological advancements, and shifting societal values (Tibbs, 2011). Vatn *et al* (2024) noted that decision-making geared towards a more sustainable and just future requires us to acknowledge the diversity of values and to balance, as well as prioritize, among competing types of values held by different people. Martin (2015) advocated for decision-making methods that provide a transparent means to value outcomes and integrate disparate information, and perceptions are the most useful in settings with a variety of stakeholders that value different outcomes. Ng (2025) for example, suggested a value-based design framework (aligned with UNSDG Goal 12 Sustainable Consumption and Production) offers a new set of measures to redefine a more prosperous and sustainable chemical process design which considers tangible and intangible impact within the selection process. The approach shared in this paper is generic enough to allow these emerging developments to be "absorbed" into the development process and operationalize in suitable learning contexts.

CONCLUSIONS

This paper proposes a model pathway for developing sustainability mindset of chemical engineering students by coupling the chemical process design and chemical product design that were traditionally taught separately in an innovative CDIO integrated curriculum exemplified by the DNA double helix comprising the key competencies for sustainability of systems thinking and values thinking. This model provides an implementable approach that can help in developing students' sustainability mindset through a suite of CDIO integrated learning experiences in an increasing level of proficiency in a progressive manner. These activities are designed – at each level of difficulty – to simultaneously bring forward the principles of sustainability mindset, applications of key competencies for sustainability to engage students in tackling sustainability challenges. The use of GenAI can support such curriculum development but requires disciplined faculty oversight. The model addressed gaps in the chemical product design education, but the generic approach presented in the design and implementation of the double helix can accommodate future developments in this important area of discourse.

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Full Disclosure: The summaries shown in Tables 1 to 4 were derived from Gemini, based on the prompts provided by the author. The entries in Table 1 have been reviewed by the author and accepted as valid for the field of chemical engineering. For Table 2, the revised descriptor for all the key competencies for sustainability were derived from Table 1 of GreenComp (pp.14-15) and earlier work by the author and colleagues (Cheah *et al*, 2025). GenAI is used to provide consistent wordings that begins with "Ability to…". Results from Table 3 were given a cursory review and found to show improved matching compared to a first iteration made under the works reported in Cheah *et al* (2025). As noted in the text, the responses produced by GenAI in Table 5, Table 6 and Table 7 need to be further validated with subject matter experts to ensure their suitability for each integrated learning experience shown. The full document – prompts and responses – is available from the link below in file "134". A point to note is that the sequence of chats with GenAI captured in the file does not necessarily match the "flow" on this paper. This is because GenAI is only used as a consultative manner and prompts entered represents the author's multiple revisions of this paper; and to write the paper per se. As such, not all outputs from GenAI were used in the writing of this paper.

https://drive.google.com/drive/folders/1h5gPaRxba899Yjk2GbR5JqJ4jeeqMqLo?usp=sharing

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Appendix A.

Table A1. Key CDIO skills & attitudes developing key competencies for sustainability

Learning Task	Key Sustainability Competencies	Supporting CDIO Skills Needed (selected items only – not exhaustive) (Can be very context-dependent such as alignment to which UNSDGs)
Year 2.1 – Plastics Reduction (General)	Systems Thinking Values Thinking	2.1 Analytic Reasoning & Problem Solving (problem identification, framing, modelling) 2.3 System Thinking (lifecycle, interactions – external to systems) 2.4 Attitudes, Thought & Learning (critical thinking, sense of urgency) 3.1 Teamwork & Collaboration (multi-perspective) 3.2 Communication (dialog and argumentation, advocacy) 4.1 External, Societal & Environmental Context (issues & values, vision for the future)
Year 2.2 – Energy Waste in Distillation (Process)	Systems Thinking Values Thinking	2.1 Analytic Reasoning & Problem Solving (quantitative modelling) 2.2 Experimentation, Investigation & Knowledge Discovery (lab modifications, testing) 2.3 System Thinking (increased complexity) 2.5 Ethics, Equity & Other Responsibilities (resource stewardship) 3.1 Teamwork & Collaboration (e.g. during experimentation) 3.2 Communication (lab reporting, safety documentation)
Year 2.2 – Eco-friendly Cleaning Products (Product)	Systems Thinking Values Thinking	2.1 Analytic Reasoning & Problem Solving (formulation design) 2.2 Experimentation, Investigation & Knowledge Discovery (testing biodegradability, toxicity) 2.3 System Thinking (interaction external to systems, trade-off) 2.5 Ethics, Equity & Other Responsibilities (health, ecological safety) 3.2 Communication (negotiation, compromise)
Year 3.1 – Water & Energy Optimization (Process)	Systems Thinking Strategic Thinking	2.1 Analytic Reasoning & Problem Solving (simulation, optimization) 2.3 System Thinking (interaction in systems, balance in resolutions) 2.5 Ethics & Responsibility (equity in resource use) 3.1 Teamwork & Collaboration (multi-disciplinary collaboration) 3.2 Communication (technical reporting, stakeholder presentations) 4.2 Enterprise & Business Context (finance & economics)
Year 3.1 – Safer Solvents (Product)	Systems Thinking Values Thinking Futures Thinking	2.1 Analytic Reasoning & Problem Solving (comparative evaluation) 2.2 Experimentation, Investigation & Knowledge Discovery (testing solvent properties) 2.3 System Thinking (life-cycle substitution impacts) 2.4 Attitudes, Thought & Learning (holding paradoxes) 2.5 Ethics, Equity & Other Responsibilities (justice, health) 3.2 Communication (regulatory foresight, consumer education) 4.2 Enterprise & Business Context (Impact on society & environment)
Year 3.2 – Circular Economy Strategy (Process)	Systems Thinking Strategic Thinking Futures Thinking	2.1 Analytic Reasoning & Problem Solving (complex system redesign) 2.3 System Thinking (closed loops, cross-sector integration: unintended consequences) 2.4 Attitudes, Thought & Learning (long-term stewardship) 2.5 Ethics, Equity & Other Responsibilities (fairness, justice) 3.1 Teamwork & Collaboration (multi-sector collaboration, networking) 3.2 Communication (policy advocacy, stakeholder negotiation) 4.1 External Context (sustainability, regulatory frameworks) 4.2 Enterprise & Business Context (vision of the future, cost-benefit analysis)
Year 3.2 – Circular Economy Products (Product)	Systems Thinking Values Thinking Futures Thinking	2.1 Analytic Reasoning & Problem Solving (strategy to solve problems: cradle-to-grave analysis) 2.2 Experimentation, Investigation & Knowledge Discovery (prototype testing) 2.3 System Thinking (trade-off, product flows, recyclability) 2.4 Attitudes, Thought & Learning (resourcefulness & flexibility in adapting to change) 2.5 Ethics, Equity & Other Responsibilities (justice, transparency, trust) 3.1 Teamwork & Collaboration (multi-sector collaboration, networking) 3.2 Communication (consumer engagement, addressing skepticism) 4.2 Enterprise & Business Context (scalability, affordability)