Fostering inclusive leadership and socio-technical skills through systems thinking and mentorship

Fostering Inclusive Leadership and Socio-Technical Skills through Systems Thinking and Mentorship

Pranav Chintalapati[1] and Naoko Ellis[1]

[1]Department of Chemical and Biological Engineering, University of British Columbia

pranav.c@ubc.ca

Abstract

This study explores the impact of collaborative learning and mentorship on systems thinking and socio-technical skill development in chemical engineering education. Through a design-based research approach, we examined a multi-year intervention in which senior students in a leadership and sustainability course mentored junior students undertaking causal analyses of industrial pollution case studies. Mixed methods were used to assess depth of reflection, causal loop diagram (CLD) construction, and open-ended survey responses across the 2023–2025 cohorts. Findings indicate that the 2025 cohort of junior students demonstrated a stronger grasp of systems thinking, with increased critical reflection, more detailed CLD modeling, and greater attention to contextual and ethical dimensions of engineering practice. Senior students also reported growth in leadership capacity, particularly in empathy, listening, and guiding others through complexity. While improvements were evident, the project is still at an early stage, with additional refinements and detailed assessments planned for upcoming years.

1 Introduction

1.1 Systems Thinking and Engineering Education

Systems thinking involves an ability to understand and analyse system behaviour, recognising both direct and indirect influences, as well as the interplay between predictable and unpredictable outcomes (Lezak & Thibodeau, 2016). It requires examining system boundaries, components, hierarchical structures, and the system as a whole; identifying interconnections and processes; recognizing emergent properties; and considering multiple perspectives in interpreting the system (Camelia et al., 2018)

In engineering education, systems thinking is increasingly emphasized as a critical competency for understanding how to navigate complex, multi-scalar challenges like climate change, resource inequities and infrastructure resilience. Systems thinking is foundational to education for sustainable development because it enables problem-solving across social, environmental and technical domains, shifting focus from isolated technical solutions to contextualized, holistic solutions. Systems thinking can also support the development of socio-technical and leadership skills, including ethical reasoning, empathy, relationality and contextual understanding.

Systems approaches offer a framework for understanding and responding to complexity (Capra & Luisi, 2014). In a recent futuring article, we propose that fostering broader systems perspectives—such as systems literacy, theory, and practice—can move students beyond simply performing life cycle analyses as applications of systems thinking. This broader lens supports key competencies in education for sustainable development by engaging ethical, epistemological, metacognitive, and ontological dimensions of learning (Chintalapati et al., 2024).

1.2 Causal Analyses of Industrial Pollution Case Studies as an Entry Point

In a 2nd-year core chemical engineering course (CHBE 264), students are introduced to systems thinking and causal loop analyses as a method for investigating root causes in global cases of industrial pollution. Students review case studies of Sacrifice Zones (Boyd, 2022) where industrial pollution has led to marginalized communities being disproportionally impacted. The students are introduced to the project initially from a chemical engineering lens of industrial safety, while tasked to assess the system from not only technical, but also social, economic and environmental perspectives through the causal loop analysis. The underlying learning objectives of exercising socio-technical and equity, diversity and inclusivity (EDI) skills are not explicitly stated at the onset of the project. Since 2024, the 2nd-year students receive guidance through interactions with 4th-year students in a leadership and sustainability course.

1.3 Leadership Training in a 4th-year Course

This course (CHBE 473) is a technical elective taken by mostly engineering students in 4th-year and graduate programmes. Technical skills development includes systems dynamics modelling and life cycle analysis. Some of the relevant learning objectives of this course include: practicing and building capacity for facing complexity and applying systems approach to societal challenges, and developing leadership qualities and skills. Each week, a servant leadership trait is explored through pre-class readings, videos, and in-class discussions. They continuously reflect on their leadership practices, applying insights from the servant leadership framework to interact with 2nd-year student teams.

Systems approaches are introduced in the context of complex social challenges and practices through CLD to stock and flow models using a system dynamics modelling tool. The students' confidence in 'guiding' 2nd-year students in their CLD development continue to increase during the term by reinforcing their knowledge in an iterative manner.

1.4 Research on Collaborative Learning

Collaborative learning is widely used in engineering education as an active learning approach that reflects the collaborative nature of professional engineering practice. Developing these skills in students is considered essential and is often an explicit learning outcome in many engineering accreditation programs (e.g., ABET, 2023, Engineers Canada, 2023). A recent literature review (Mercier et al., 2023) examining studies from 2010 to 2022 on collaborative and cooperative learning in engineering education outlines both the needs and challenges in this area. Notably, the review identifies key obstacles, including the complexity of effectively implementing and studying collaborative learning in classroom settings, an overreliance on student attitudes as indicators of success, and a lack of research on the long-term development of collaborative competencies, particularly around student reflection and metacognitive awareness of effective group processes.

Through a unique pedagogical opportunity of having 4th-year leaders interacting with 2nd-year teams throughout a systems analysis assignment, we are exploring how collaborative learning may cultivate core 21st-century competencies, such as critical thinking, ethical leadership, and navigating complexity, in both levels of students.

2 Methodology

The study emerges from a few years of conducting exploratory research using the design-based research model, i.e., iteratively learning and adapting through the cycles of exploring, testing, reflecting and learning (Anderson &Shattuck, 2012). This paper reports on the testing and reflecting phase where a few assessment methods are tested for further research process improvement. Mixed method is applied to collect and analyse observational data, allowing convergent parallel design when triangulating both quantitative and qualitative data (Crewell & Plano Clark, 2017).

Data for this study are collected as part of two courses described above. At this early stage of evaluation, we are reporting on observations of aggregated, anonymized data from entire cohorts of classes. For CHBE 264, students (identified as junior students) produced causal loop diagrams, poster presentations, group reflections and feedback on CHBE 473 students (i.e., senior students); while, for CHBE 473, students produced reflections on their leadership activities, and their perception of CHBE 264 students' systems thinking skills.

CHBE 264 reflection data was anonymized and aggregated for the 2024 and 2025 cohorts. The reflection documents were then qualitatively coded for depth of reflection using a simple 4-level rubric developed by adapting methods described by Kember et al. (2008) and Wald et al. (2012). The rubric, shown in Table 1, uses indicators defined based on learning goals of the assignment.

Table 1: Reflection assessment rubric

	Level	Description
1.	Descriptive	Descriptions without much interpretation. Summarizes what was done with little insight.
2.	Introspective Understanding	Begins exploring personal reactions; consideration for multiple viewpoints; recognition of other perspectives or implications.
3.	Engagement	Connects ideas and begins analysing patterns and feedback; considers broader social and environmental implications, with some recognition of structural issues or inequities.
4.	Critical	Analyses underlying assumptions and contextual factors; thoughtfully examines social and systemic issues, including power dynamics, personal biases and values; demonstrates deeper understanding of complexity

CHBE 264 CLDs were evaluated for number of feedback loops identified in the system. Although the presence of more factors within CLDs is not necessarily a better representation of the system, the presence of more feedback loops may indicate a deeper analysis of the interactions between factors. Recognition of feedback loops may provide more emergent understanding of how the system behaves. The number of feedback loops was assessed in CLDs from 2023 and 2025, representing cohorts before and after collaboration with CHBE 473 was introduced. Anonymous survey responses from the same cohorts were also aggregated and qualitatively analysed for language related to: 1) systems thinking, 2) EDI awareness, 3) going beyond technical solutions, and 4) socio-technical and leadership skills.

CHBE 473 students engaged in a structured leadership development process grounded in the servant leadership framework. At the beginning of the course, students completed a self-assessment, articulating their leadership vision. Over the term, they submitted four guided reflections on their leadership experiences with junior teams. Final reflections and open-ended survey responses were qualitatively analysed for evidence of systems thinking, leadership growth, and recognition of change in the junior students they were guiding.

3 Results and Analysis

3.1 Assessment of CHBE 264 Reflections

Although both the 2024 and 2025 CHBE 264 cohorts interacted with CHBE 473 students (reflections were not assigned in 2023), there were notable differences in implementation. Primarily, the number of groups each CHBE 473 leader had to guide was reduced from two to one. For this reason, we were curious to what extent changes in depth of reflection may be observed between the 2024 and 2025 cohorts. CHBE 264 reflection reports were qualitatively coded for four levels of reflection (Table 1). The findings show that most of the reflection content for both cohorts is largely descriptive. However, the 2025 cohort showed, on average, relatively higher proportions of deeper levels of reflection. The 2024 reflections more frequently propose solutions detached from implementation within the existing system, whereas the 2025 reflections more frequently discuss the struggle to identify direct solutions due to the complex dynamics of their systems. In demonstrating a deeper understanding of the complexity of their cases, the 2025 reflections more frequently acknowledge that incremental, small-scale shifts are more likely to be implementable than silver bullet solutions. Comparing the two cohorts further, roughly 1/3rd of the content in the 2025 reflections demonstrates levels of reflection beyond descriptive statements, compared to only 15% of the content in the 2024 cohort reflections. Of that more reflective content, the 2025 cohort shows a higher proportion of critical reflection (17% vs. 4%), shown in the pie charts of Figure 1.

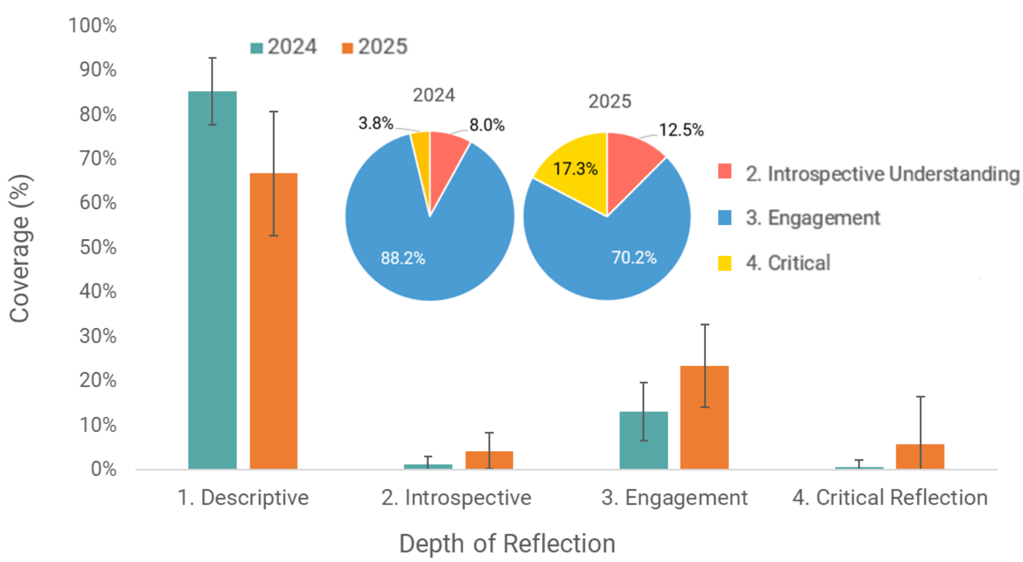

Figure 1: Percent of content at different levels of reflection for 2024 and 2025 CHBE 264 cohorts

3.2 CLD Comparison Between 2023 and 2025 in CHBE 264

A high-level comparison of the average number of feedback loops in the CLD analyses of the 2023 and 2025 cohorts shows a marginal increase, from 4.6 ± 1.9 (2023) to 6.5 ± 3.6 (2025), since the integration of leadership interactions. There were nine instances where the same case study was investigated by groups in the 2023 and 2025 cohorts. We assessed the change in the number of feedback loops in these common case studies between the two cohorts, and found that five showed an increase (+5.3 avg.), three showed a decrease (-2.8 avg.) and one instance showed no change. An assessment of the CLD analyses from each cohort also revealed an improved understanding of the CLD process by the 2025 cohort. By comparison, the 2023 cohort more frequently had labelled enclosed portions of their CLDs as feedback loops when there was in fact no feedback. Since the CHBE 473 students are taught CLDs and systems analyses in more detail and over a longer period than the CHBE 264 students, there's some indication that the interactions between the senior and junior students has helped improve the latter's systems thinking skills in the CLD analysis.

3.3 Comparison of 2023 and 2025 CHBE 264 Survey Responses

At the end of the CHBE 264 course in 2023 and 2025, students were asked to provide an anonymous open-ended response to the question "Why do you think you were asked to do the poster project?", with references to systems thinking or industrial pollution case studies intentionally withheld from the question to avoid biasing their response. Responses from both cohorts (similar response rate of n=44 for 2023 and n=41 for 2025, i.e., ~40% the class sizes) were qualitatively analysed. The results showed an improvement in multiple thematic areas of interest in responses by the 2025 cohort. The 2023 responses more frequently referred to developing an understanding of real-world consequences of their work and importance of the decisions that they may make as engineers. The focus appears to be more geared towards a general sense of engineering impacts and the importance of knowledge acquisition with more of a technical orientation. The 2025 responses more directly discuss systems thinking, holistic understanding and contextualized problem solving. They also showed more frequent use of terms related to complexity, critical thinking, ethics and context, while noting the limitations of purely technical solutions. Across the four thematic areas of interest (see Methodology), the 2025 responses showed significant increase in language related to systems thinking, some improvement in the importance of looking beyond the technical solution, and a moderate increase in socio-technical and leadership skill development through indications of growth and self-awareness. Interestingly, EDI-related outcomes were less frequently cited in the survey responses of both cohorts, despite being highly prominent in reflection reports, which frequently discussed power dynamics, environmental injustices, marginalization, racism and ethical responsibilities.

3.4 Senior Student Reflections on Their Leadership

As part of their leadership practice assignment, senior students began by completing a self-assessment using the servant leadership framework and setting personal purpose and vision for leading 2nd-year student teams. Throughout the term, they submitted four formal reflections guided by prompts related to their leadership experiences. Many students noted a significant shift in their understanding of leadership—from viewing it as an authoritative role to embracing mentorship and servant leadership qualities. For several students, this was their first time leading a team rather than working alongside peers. Initially, they were uncertain about how much direction to provide or control to exert. Some expressed frustration when their 2nd-year teams appeared disengaged or unmotivated. However, over the eight weeks of collaboration, most leaders and their teams developed a good rapport in their interactions and communication.

Several student leaders had taken the same 2nd-year course themselves two years prior and reflected on recognizing aspects of their past selves in the student teams they were now leading. This awareness prompted them to be more intentional in their listening—consciously setting aside prior knowledge and assumptions to better understand their teams' perspectives. Many noted that the 2nd-year students were struggling with similar challenges they had once faced, particularly the heavy workload and the sense of being far from graduation. These shared struggles resulted in a greater sense of empathy. In response, the student leaders emphasized the importance of being present, actively listening, and offering support as their teams navigated their own journeys.

A word cloud generated based on senior students' final leadership reflections (n=26) (not shown for space) included relevant leadership traits such as empathy, listening, humility, and grow/growth (based on growth of others).

3.5 Senior Student Survey on Observed Shifts in Junior Students

Senior students who responded to the survey (23/29) noted their gaining knowledge in and practice of systems approaches through this course. When asked how they have noticed this shift, many commented on their own ability to think more holistically with considering impacts, interconnected parts, and additional issues emerging. They also noted their increased capacity in not yet knowing or dealing with ambiguity. Many have commented on how their ability to think in systems had improved the way they think about their future and make decisions in their everyday lives.

In fact, many senior students effectively demonstrated their understanding of systemic interactions and the application of systems thinking by analysing a case study and illustrating how to navigate the uncertainties and ambiguities that inherently arise when working with complex systems as part of an essay-based final exam question.

The survey also asked senior students whether they observed junior students developing a stronger understanding of systems approaches, and how they recognized this growth. Senior students noted that their teams often articulated systems thinking by emphasizing the interconnectedness and complexity of their cases. Many junior students reflected on how multiple elements were linked to their identified sacrifice zones, demonstrating a more holistic perspective and an improved ability to see how different parts of a system interact. One senior student shared that their team came to recognize the absence of a single "correct" answer, highlighting their deeper engagement with the ambiguity inherent in complex systems. Another noted how the junior student team considered direct and indirect effects in the CLD and analysed it considering various scenarios.

3.6 Impact of Mentorship on Learning Outcomes

This collaborative learning project provided students with an opportunity to engage with the complexity of real case studies by constructing CLDs. For senior students, this required not only deepening their own understanding but also learning enough to effectively teach the concepts to their junior teams. The process was inherently iterative as teaching became a powerful form of learning, and guiding their teams through the development of CLDs reinforced the senior students' own grasp of the methodology and its application to complex systems.

Preliminary triangulation of reflections from both senior and junior students reveals some gaps in their collaborative learning experiences. Overall, senior students reported growth in their ability to facilitate the development of systems thinking skills among junior students through guiding the construction of CLDs. Many described their role as leaders needing to adapt to the evolving dynamics within their teams.

Conversely, junior students generally expressed appreciation for their leaders, while also identifying areas for improvement, such as more structured meeting scheduling and more efficient use of time. A common request among junior students was for more specific, detailed feedback on their CLDs. Meanwhile, senior students noted that they were often mindful of not overstepping or micromanaging, striving to strike a balance between offering support and maintaining autonomy of their teams.

3.7 Future Directions and Study Limitations

Based on the design-based research model, this study is positioned as a preliminary cycle of learning, where some of the data collection and analysis are to inform the next cycle of iteration. We have learned that having more structured time between the classes would allow senior and junior students to engage with less pressure on time management. There may be ways to manage expectations of both sides as students engage in their respective assignments. While striking a balance between how much senior students should guide the CLD and allowing autonomy and learning to unfold for junior students, there is room to clarify their roles. The perception among junior students that leaders who previously completed CHBE 264 are better suited to guide them through the assignment warrants further exploration.

When senior students were asked how they could recognise growth in their junior team members' practice of systems approaches, their responses offered valuable insights into the seniors' own understanding of systems thinking and complexity.

Throughout the term, many senior students built constructive and supportive relationships with their junior teams. Several expressed a deep sense of pride when attending their junior teams' final poster presentations. In some cases, a genuine sense of co-learning emerged, revealing a potential for deeper inquiry into collaborative pedagogy. Moving forward, we aim to build on these findings to develop a pedagogical framework that fosters and supports meaningful collaborative learning experiences.

As CHBE 473, the senior leadership course, has only been offered for the second time, the availability of comparative data remains limited as the course continues to evolve. Additionally, the absence of ethics approval at this early stage of this project has limited data analysis to instructor observations of aggregated data.

4 Conclusions

A preliminary assessment of the integration of cross-course collaborative learning appears to demonstrate a positive impact on the inclusive leadership and socio-technical skills of the students involved. Reflections, open-ended surveys and causal loop diagrams of junior students demonstrate deeper engagement with the complexity of their case studies and improved recognition of the limitations of isolated technical solutions. Reflections demonstrated more frequent critical insights and broader considerations of systemic, structural and social implications of their case studies. Senior students were able to observe and articulate shifts in the junior students' understanding of complexity, while demonstrating an understanding of their own role in supporting that process. The leadership model appears to have supported mutual learning, though it also revealed the need for clearer role definition and more iterative project structures. Despite some limitations in available data, this first cycle of a design-based educational intervention highlights the value of collaborative, systems-oriented pedagogy in fostering ethical, reflexive, and inclusive engineering mindsets. Future work will focus on refining the leadership structure and increasing time for iterative learning.

5 References

ABET. (2023). Criteria for accrediting engineering programs: Effective for reviews during the 2025–2026 accreditation cycle. ABET. https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2025-2026/

Anderson, T., & Shattuck, J. (2012). Design-based research: A decade of progress in education research? *Educational researcher, 41*(1), 16-25.

Boyd, D. R. (2022). Sacrifice Zones: 50 of the Most Polluted Places on Earth. Based on a report presented to the UN Human Rights Council, A/HRC/49/53.

Camelia, F., Ferris, T. L. J., & Cropley, D. H. (2018). Development and initial validation of an instrument to measure students' learning about systems thinking: The affective domain. *IEEE Systems Journal, 12*(1), 115–124.

Capra, F., & Luisi, P. L. (2014). The systems view of life: A unifying vision. Cambridge University Press.

Chintalapati, P., Evans, G., Gladwin, D., Jamieson, M., & Ellis, N. (2024). Shaping futures: A dialogue on chemical engineering education. *The Canadian Journal of Chemical Engineering, 102*(5), 1688-1704.

Creswell, J. W., & Clark, V. L. P. (2017). Designing and conducting mixed methods research. Sage publications.

Engineers Canada. (2023). Accreditation criteria and procedures 2024. https://engineerscanada.ca/sites/default/files/2024-11/Accreditation_Criteria_Procedures_2024.pdf

Kember, D., McKay, J., Sinclair, K., & Wong, F. K. Y. (2008). A four-category scheme for coding and assessing the level of reflection in written work. *Assessment & Evaluation in Higher Education*, *33*(4), 369–379.

Lezak, S. B., & Thibodeau, P. H. (2016). Systems thinking and environmental concern. *Journal of Environmental Psychology*, 46, 143–153.

Mercier, E., Goldstein, M. H., Baligar, P., & Rajarathinam, R. J. (2023). Collaborative learning in engineering education. In *International handbook of engineering education research* (pp. 402-432). Routledge.

Wald, H. S., Borkan, J. M., Taylor, J. S., Anthony, D., & Reis, S. P. (2012). Fostering and evaluating reflective capacity in medical education: developing the REFLECT rubric for assessing reflective writing. *Academic medicine: journal of the Association of American Medical Colleges*, *87*(1), 41–50.