Pre- and post-module assessment of improvement in systems thinking among design engineering students: an interactive case study-based approach

Pre- and Post-Module Assessment of Improvement in Systems Thinking among Design Engineering Students:

An Interactive Case Study-Based Approach

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Abstract

With the increasing need for holistic approaches to tackle complex, real-world problems, this study focuses on understanding students' systems thinking capabilities within sustainable engineering education. This paper examines the impact of one interactive, case study-based module on developing systems thinking skills among design engineering students. It evaluates their pre- and post-module progress in applying systems thinking principles to challenges like climate resilience and disaster mitigation. The module was implemented for second-year BEng students in UK for a multidisciplinary design engineering program and applied to a real-life case study which focused on flood mitigation strategies in Australia. The students were supported to adapt the learning from the case study and adapting the insights to the project within the students' curriculum. The research employs a mixed-method approach, combining quantitative and qualitative data collection. A pre-module survey assessed students' baseline understanding of systems thinking, including their self-evaluated knowledge, confidence in addressing complex problems, and collaborative approaches. Post-module surveys and selective interviews provided insights into changes in understanding and learning experiences after completing the module. Statistical analysis of pre- and post-module data revealed measurable (self-assessed) improvements in systems thinking skills, particularly in recognising interconnections, managing uncertainty, and appreciating diverse stakeholder perspectives. However, students reported feeling overwhelmed by the introduction of multiple frameworks and definitions, highlighting the need for careful facilitation to avoid cognitive overload. Qualitative feedback highlighted the module's positive impact on students' confidence and their ability to apply systems thinking frameworks to complex problems. Students valued the use of real-world scenarios and recommended adding case studies on topics like fire and storm mitigation to expand their learning. This study highlights the value of case study-based, interactive learning in embedding systems thinking within engineering education. By bridging the gap between academic theory and practical application, the module equips students with essential skills for navigating global challenges. The findings contribute to the evolution of engineering curricula, demonstrating the scalability and relevance of similar approaches across diverse educational contexts.

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1 Introduction

Engineering solutions for sustainability and resilience often fail to fully account for the complexity of real-world systems. Extreme climate events, such as floods and wildfires, have highlighted the limitations of traditional engineering approaches that focus on isolated technical solutions rather than interconnected socio-technical systems. A growing body of research emphasises the need for systems thinking in engineering education to equip future engineers with the ability to navigate these complexities (Godfrey, Crick & Huang, 2014; Monat, Gannon & Amissah, 2022). As defined by multiple literatures and their review, "Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them to produce desired effects. These skills work together as a system." (Arnold & Wade, 2015).

Systems thinking has emerged as a crucial competency in engineering education, enabling future engineers to navigate these complexities by recognising interdependencies, anticipating unintended consequences, and developing holistic solutions. As shown across multiple literatures, system thinking is a widely impactful method when integrated in various engineering curriculum (Spain, 2019).

However, while research increasingly advocates for integrating systems thinking into engineering curricula, significant gaps remain in structured assessment methods that evaluate students' ability to apply these principles in real-world scenarios (Dugan, et. al, 2022; Claesson, 2015). Existing educational approaches, such as project-based and case study-based learning, show promise in fostering systems thinking, but their effectiveness requires further investigation, particularly in terms of measuring learning outcomes and addressing cognitive load challenges when introducing multiple frameworks (Aristidou, 2020; Emblen-Perry, 2022).   .

This study aims to assess the impact of an interactive, case study-based module on students' ability to apply systems thinking in engineering problem-solving. The central research question guiding this work is: **How does an interactive, case study-based module impact students' ability to apply systems thinking in engineering problem-solving?** By answering this question, this research evaluates the impact of an interactive, case study-based module on students' systems thinking skills by assessing their progress before and after engagement. It also examines the key challenges students face in applying systems thinking principles to complex engineering problems, providing insights into how such educational interventions can enhance their analytical and problem-solving abilities.

2 Background and context

The study was conducted with second-year undergraduate engineering students enrolled in a global design engineering programme at TEDI-London, which integrates a blended learning pedagogy, combining physical facilities for design, prototyping, and collaboration with digital learning materials and remote collaboration tools like an online Learning Management System (LMS) and Microsoft Teams. The study was developed in collaboration with the Royal Academy of Engineering's EngineeringX initiative, which aims to tackle this by having more people develop a systems mindset and to use systems approaches to handle complexity that comes with these challenges.

The module which is at the centre of this study was designed to enhance students' ability to analyse complex engineering problems through a socio-technical systems lens by integrating project-based and inquirydriven learning, blended learning methods, and interactive tools. Interactive tools such as AI-driven chatbots, scenario-based assessments, and narrative-driven exercises engaged students in a dynamic, applied problem-solving environment, reinforcing their ability to recognise interdependencies and develop holistic engineering solutions. As the case study, the module examined climate resilience in urban transport systems. It specifically explored the response of the Queensland Reconstruction Authority (QRA) to the 2010–2011 floods in Australia, analysing how its role evolved from short-term asset repairs to long-term hazard management and community-focused resilience planning. The module's focus on extreme climate events within urban environments provided a practical framework for students to analyse, collaborate, and devise holistic solutions.

For this paper, while there is no universally agreed-upon definition of systems thinking, a working interpretation has been drawn from multiple sources to support the learning objectives of this module, particularly in evaluating systems thinking competencies. Systems thinking is commonly described as a framework or approach that enables a deeper understanding of the dynamic relationships among interconnected elements within a system and the external influences that shape them (Government Office for Science, 2023; Design Council, 2021). It promotes a holistic view that considers the interactions, feedback loops, and evolving patterns within the system, rather than isolating individual parts. Systems thinking requires practitioners to reflect on how elements such as people, organisations, and governments interact over time, recognising that any intervention can trigger a cascade of effects—potentially reinforcing or transforming the system. Likewise, it is highlighted that systems thinking as both a conceptual framework and a discipline for identifying systemic interconnections and understanding the structural causes behind complex challenges. Appendix 1 which lays down the pre- and post-module assessment questions lays out the definition in more details.

3 Methodology

This study employed a structured, interactive blended learning intervention developed through a collaborative effort between academics, case study authors, and learning designers from various institutions. The intervention was developed using an e-learning platform, and consisted of three online modules: Context, Analysis and Insights, and Discussion and Transferable Learning, each requiring approximately 1 to 2 hours of engagement.

The learning design was informed by Diana Laurillard's Learning Types (Laurillard, 2013), ensuring a balanced integration of acquisition, inquiry, discussion, practice, and collaboration to create a well-rounded pedagogical approach. The modules were structured around a narrative-driven experience, where students assumed the role of an advisory team tackling global disasters. A fictional guide, 'Bernice,' facilitated the learning journey, providing direction and context.

The modules incorporated high-quality explainer animations to break down complex concepts, alongside interactive maps, timelines, and hotspot infographics for exploratory learning. Practice activities, including sorting tasks and quizzes, reinforced key information and supported knowledge retention through active engagement. The learning objectives were designed to provide students with a broad understanding of the complexity of systems thinking, fostering problem-solving and decision-making skills, specifically for students to apply the insights. To deepen learning and encourage real-world application, scenario-based assessments were integrated into the course. These assessments presented authentic problem-solving situations, requiring students to apply theoretical knowledge through collaborative group work, enhancing their critical thinking and systems-thinking abilities.

Additionally, the modules featured role-play exercises leveraging AI chatbot technology, where students engaged in debates with a sceptical AI to secure funding for flood mitigation strategies. These interactive exercises allowed learners to simulate real-world decision-making processes, reinforcing their practical understanding of complex systems and stakeholder negotiations.

The study employs a mixed-method approach to evaluate the effectiveness of the module in fostering systems thinking.

1. **Pre-Module Assessment:** A survey (check Appendix A) was conducted to gauge students' baseline understanding of systems thinking, including their ability to identify interconnected elements, approach collaborative problem-solving, and handle uncertainty. Students also self-assessed their confidence in addressing complex engineering challenges. 26 students filled this survey.
2. **Interactive Module Design:** The module incorporated real-world case study on climate resilience and disaster mitigation implemented in Queensland for flood mitigation. Students worked in collaborative teams to explore stakeholder interdependencies, dynamic relationships, and decision-making strategies. The module was partially based on instructions, while partially based on self-paced learning for the students. A facilitators guide is provided in the Appendix B and a suggestive timeline of how to facilitate the module is laid down in Appendix C. For this group of students, as the systems thinking module was integrated in an already running module based on a large-scale renovation project, the case study was further developed to be applied for a systems resilience solution for this renovation project.
3. **Post-Module Assessment and Interviews:** After completing the module, students were reassessed using a post-module survey. To deepen insights, selective interviews were conducted, capturing qualitative feedback on the learning experience and its practical applications in ongoing projects. 12 of those 26 students who filled the pre-module survey, filled this post-module survey.

Data collection and analysis involved both quantitative and qualitative methods to evaluate the module's effectiveness. Statistical analysis was conducted on pre- and post-module survey responses to measure changes in students' understanding, attitudes, and skills, allowing for the identification of trends and overall learning impact. In addition, thematic analysis of qualitative feedback provided deeper insights into students' experiences, highlighting recurring themes, perceptions, and suggestions for improvement. This mixed-methods approach ensured a comprehensive evaluation of the module from multiple perspectives.

4 Results and Discussion

Overall**,** preliminary results indicate significant improvement in students' systems thinking capabilities. Figures 1-2 are the histograms and frequency box plots respectively showcasing the change in understanding of the students, based on the pre and post the module surveys. Understanding is measured as an ordinal scale of 0-5 of increasing understanding of the 12 students, self-evaluated by the students, in the surveys. So, a value of 1 of change in understanding depicts a positive but lesser change in understanding compared to value of 2. While a 0 or lower value indicates not a change in understanding.

As seen in figure 1a (left), students had an improvement in the understanding of systems thinking. Also, note that these students already know the concept of systems thinking from year 1, so there is not a significant increase in understanding (i.e. the average change in understanding on this scale is around 0.25). Though as can be seen in figure 1a (right), there is a higher positive range (with up to 3 for some students) of improvement in understanding definitions of systems thinking. As the number of positive changes in understanding is higher at the right side of figure 1a image, it shows that when applied to the case study, students understand the concept of systems thinking better. At the same time, as there are multiple definitions for systems thinking to understand, they tend to get a bit overwhelmed, when applied to a case and as seen in figure 1b (right), their understanding of overall definitions reduces to some extent.

When looking at each definition in depth, figure 2 (next page) shows some insights. There is more clarity in the context of all definitions when applied to case study, and especially the context of uncertainty and diversity of stakeholders are understood well. At the same, case study can add to feeling bit more overwhelmed due to the multiple aspects in the modules e.g. the introduction of Cynefin framework (Nachbagauer, 2021) and its various definitions as well.

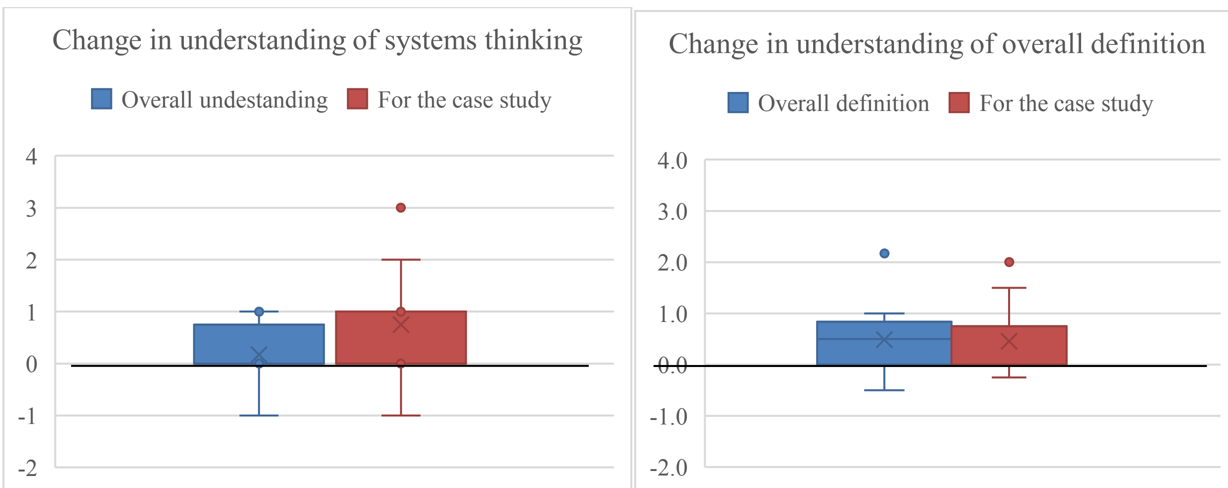

Figure 1 (a-b): Change in understanding of overall definition and system thinking (nominal scale of 0-5 of increasing understanding of the 12 students, self-evaluated in the surveys)

4.1 *Quantitative Analysis*

The survey data showed a clear, measurable improvement in students' understanding of systems thinking concepts. Through statistical analysis, self-assessed gains were validated in several key areas. Students reported enhanced abilities to recognize and analyse interconnected components within complex systems. They also demonstrated a better understanding of the importance of diversity in team dynamics when approaching problem-solving tasks.

Another significant improvement was seen in students' ability to cope with the uncertainty that is often present in real-world engineering challenges. This suggests that the module was effective in building confidence and competence in navigating complexity. In addition to these improvements, many students expressed a strong interest in exploring a wider variety of case studies. Specific topics suggested included fire mitigation strategies and responses to storm-related scenarios. This feedback highlights the value of expanding the current case study collection to include a broader range of complex engineering problems that reflect real-world challenges.

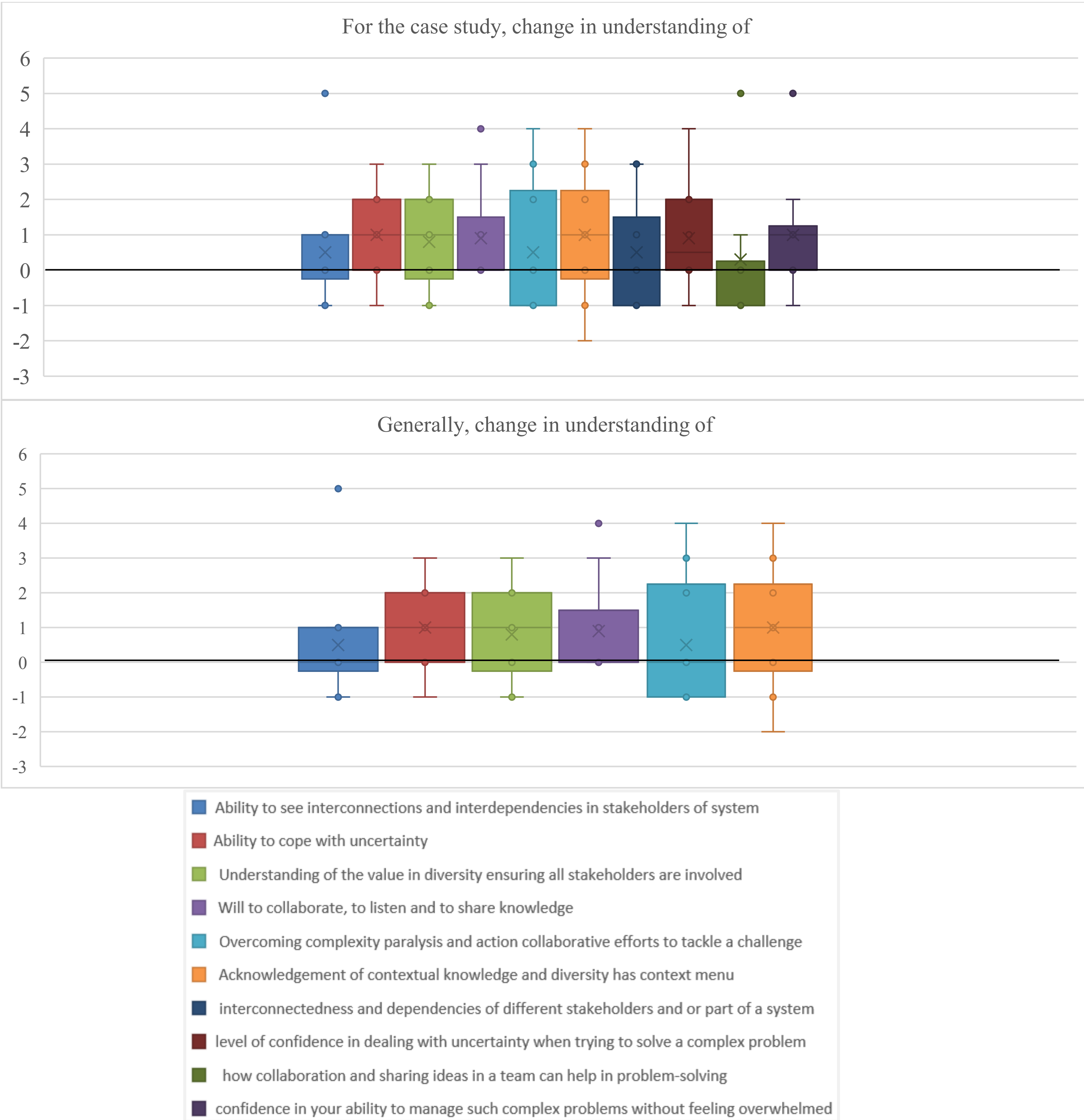

Figure 2: Change in understanding (nominal scale of 0-5 of increasing understanding of the 12 students, self-evaluated in the surveys) for the definition of system thinking

4.2 Qualitative Feedback

Interviews revealed a marked increase in students' confidence when applying systems thinking frameworks. They demonstrated a deeper appreciation for the complexity of engineering problems and the importance of holistic approaches. Specific feedback emphasised the module's relevance in contextualising theoretical principles through practical case studies.

Student feedback provided valuable insights into the effectiveness of the module. Many students appreciated the real-world relevance of the content and found the practical application of systems thinking frameworks particularly engaging and useful. They highlighted that the module helped bridge theoretical concepts with real engineering challenges, enhancing their overall learning experience.

However, some challenges were also identified. A recurring theme was the experience of cognitive overload, largely due to the introduction of multiple frameworks and definitions in a short period. While these tools were seen as useful, students suggested that the delivery could be refined to support better understanding and application.

The strengths of the module lay in its strong connection to real-world problems and its ability to make abstract systems thinking concepts more tangible and applicable. Students valued the hands-on approach and the opportunity to engage with complex, interdisciplinary issues.

To improve the learning experience, students recommended refining facilitation strategies—such as pacing the introduction of concepts more gradually—and simplifying the number of frameworks presented. Addressing these areas could help reduce cognitive load and support deeper engagement with the content.

5 Conclusion

The findings underscore the value of interactive, case study-based learning in embedding systems thinking within engineering education. By engaging students in realistic scenarios, the module bridges the gap between academic theory and practical application. Students reported feeling more equipped to tackle issues related to climate resilience, disaster mitigation, and urban sustainability.

The success of the module demonstrates its scalability and relevance across diverse educational settings. Institutions can adopt similar case study-driven approaches to empower students with the skills needed for sustainable development and complex problem-solving. The research contributes to the ongoing evolution of engineering education, advocating for innovative, context-driven teaching methodologies.

5.1 Summary of Key Findings

The case study-based approach had a significant impact on developing students' systems thinking skills. By engaging with real-world scenarios, students were able to better understand the complexity of interconnected systems, apply theoretical frameworks in context, and reflect on diverse perspectives and uncertainties. This method encouraged critical thinking, collaboration, and the practical application of abstract concepts.

Students identified several benefits, including the relevance of the module to real engineering challenges and the opportunity to practice systems thinking in a structured yet flexible environment. At the same time, challenges such as cognitive overload and the need for more streamlined facilitation were noted, suggesting areas for future refinement.

Interactive learning played a crucial role in bridging the gap between academic theory and practical application. By using real-world case studies, the module enabled students to engage more deeply with complex, sustainability-focused problems, fostering both analytical and collaborative skills. This approach contributes meaningfully to the ongoing evolution of engineering education, supporting the development of future engineers equipped to address global sustainability challenges through systems thinking and interdisciplinary problem-solving.

5.2 Implications for Engineering Education

The findings from this module have several important implications for the future of engineering education. One key recommendation is the integration of systems thinking more deeply into engineering curricula. Embedding these concepts throughout the program—rather than in isolated modules—can help students develop a more holistic and adaptive mindset, better preparing them for the complexities of modern engineering challenges.

The module also demonstrated strong potential for scalability and transferability. Its structure and content could be effectively adapted for different educational contexts, including other universities and professional industry training programs. This flexibility supports the broader adoption of systems thinking principles across the engineering discipline. Looking ahead, there are plans to expand the library of case studies to cover a wider range of real-world scenarios. Future developments include the incorporation of additional examples such as fire mitigation and storm-related challenges. These additions aim to enrich the learning experience by offering diverse, complex problems that reflect the dynamic nature of engineering practice.

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Appendix A - Survey questions

Pre- and post- module assessment questions: the pre-module assessment questions check the initial understanding of the students and are listed below, while the post-module assessment ones are a bit modified version of these questions, evaluating the improvement in the understanding of students.

Systems thinking definition - general understanding

Answer these questions from a more general understanding of the way you apply systems thinking in your group work for different projects.

1. How well do you understand the concept of systems thinking in general?

Likert scale question (1 = No understanding, 5 = Very strong understanding)

0. In your own words, what do you think are complex problems and what makes solving complex problems difficult?

0. How do you currently approach solving complex problems, and have you worked with others to do so?

0. How do you think systems thinking could improve your approach to problem solving or decision making in your field of study?

Systems thinking definition - contextual understanding

Apply these questions in the context of extreme heat or a fire event around Printworks, in Canada Water. Think how you would apply the systems thinking context in such a scenario.

0. How well do you understand the concept of systems thinking for the scenario? *Likert (1 to 5)*

0. What among the following do you think constitute systems thinking? *Likert (1 to 5)*

    . Ability to see interconnections and interdependencies, spot patterns, dynamic human relationships, learning as developmental and relational, emergent questions

    . Ability to cope with uncertainty

    . Understanding of the value in diversity ensuring all stakeholders are involved

    . Will to collaborate, to listen and to share knowledge

    . Overcoming complexity paralysis to understand lever points and action collaborative efforts to tackle a challenge

    . Acknowledgement of contextual knowledge and diversity has context menu

Systems thinking elements

Apply these questions in the context of extreme heat or a fire event around Printworks, in Canada Water. Think how you would apply the systems thinking context in such a scenario.

Likert Scale Questions (1 = No understanding, 5 = Very strong understanding)

0. For this context, how well do you understand the interconnectedness and dependencies of different stakeholders and.or part of a system?

0. For this context, if you were a stakeholder involved with Printworks project, what is your level of confidence in dealing with uncertainty (unlikely scenario) when trying to solve a complex problem like extreme heat or fire around Printworks?
0. For the same context, how well do you understand how collaboration and sharing ideas in a team can help in problem-solving?
0. For this context, if you were a stakeholder involved with Printworks project, how confident are you in your ability to manage such complex problems without feeling overwhelmed?
0. For the same context, how confident are you in ensuring diversity of stakeholders involved is acknowledged?

Appendix B – Facilitators guide (example screenshot)

FACILITATORS GUIDE

By following this guide, facilitators will be equipped to deliver the course effectively, ensuring that participants are engaged, informed, and able to apply their learning to real-world scenarios.

I. Introduction

1. Welcome and Orientation

Welcome participants A. Begin with a warm welcome to all participants. B. Introduce yourself as the facilitator. C. Contextualise the case study, and highlight the importance of course and its relevance to complex engineering problems and systems thinking.	*Suggestive text: Welcome student, to this online course centred around the case study "Australian Climate Extremes and Building Transport Network Resilience" by Dr. Kristen MacAskill, Dr. Marlies Barendrecht, and Dr. Catherine Tilley.* *I am … and I would be facilitating this course for you while you navigate through the online pages on the provided link. We will talk about the technical details of accessing the online content very soon (check next section on "technical requirements").* *During this course, you will explore the evolution of the Queensland Reconstruction Authority's role in enhancing the resilience of Queensland's road network post-floods, gaining insights into safer complex systems and infrastructure management.*
Course objectives and outcomes A. Potentially start a SpeakUp room, where you can collect ideas from students on a. What are systems thinking in your opinion? b. Why is systems thinking relevant (for the project we are working on/ engineering solutions)?	*Suggestive text for points B and C: The course is divided into three modules to guide you through this case study and equip you with essential skills applicable across various contexts related to systems thinking.* *By the end of this learning journey, you should have:* • *Developed an understanding of when systems approaches are relevant within specific contexts.* • *Acquired the skills to apply systems thinking methodologies effectively in problem-solving and decision-making.*
B. Provide a brief introduction and/or examples of complex engineering problems and the need for systems thinking for them. C. Explain the course objectives: a. Develop an understanding of systems approaches in specific contexts. b. Acquire skills to apply systems thinking methodologies in problem-solving and decision-making.	*Module 1: Understand the context, history, and complexity of Queensland's Reconstruction Authority and Infrastructure Resilience in Disaster Management.* *Module 2: Explore challenges, funding arrangements, and the dynamics of knowledge exchange in Disaster Resilience.* *Module 3: Explore the power of connections and the essentials of effective leadership in Disaster Resilience.* *The first and third modules include both group and individual assessments with respective handouts for working on resilience building based on a scenario. Either assignment can be conducted based on the setting: Group assignment is for an in-person setting, while individual is for online-only setting. The second module involves a bot-based discussion on resilience funding.*

2. Technical requirements for online content
   - Instructions for accessing course materials and joining virtual sessions
     i. The course is available to access here: https://engineeringx.tedi-london.ac.uk/. This link may be shared with students in your institution's preferred way (e.g. A post via your institution's VLE for student communication platform). The site is optimised for access via desktop and mobile devices
     ii. Modules 1-3 within the course can be accessed via the home page of the website, and also from the top navigation bar on the website. Each module is a self-contained series of digital content that is hosted on a single page within the site. Students can move through the content by scrolling down the page. There are action buttons to 'Continue' at various points in the content after learning activities are completed.
     iii. In case of any technical issues with the pages, please contact laurence.chater@tedi-london.ac.uk

Appendix C – Timeline touchpoints (example screenshot)

A	B	C	D	E	F
		Expected time requirements	Independent tasks of students	Student discussion with the group	Touch base with module instructor
Module 1 (4 hr)		5 min	Read the section		
	About (15 min)	10 min	Watch the video and reflect		
		10 min	Watch video 1 and reflect		
		2 min + 3 min	Watch video 2	Discuss their understanding about the case in the group	
	The context (30 min)	5 min + 10 min	Browse through the map		Module lead discusses the map related questions posed in the module in the whole class "Can you outline how the flooding might have impacted the connectivity of different regions within Queensland?" "In what ways do you think the events prompt or necessitate a shift in thinking towards a more comprehensive systems approach to road transport safety?" *Tip - bring in the relevant case related information from the videos*
		5 min	Watch video 1 and reflect		
		10 min	Click on the timeline prompts and reflect		
		10 min + 10 min + 10 min	Watch video 2	Discuss with group what they understand as QRA's role	Prompt questions for discusison in the class: "How different events reformed the QRA a permanent entity?" "Why was QRA's formation important to mitigate future events"
		10 min + 10 min + 10 min	Watch video 3	Discuss with group what they understand of cynefin framework and how does this follow for QRA's approach	Prompt questions for discusison in the class: What made the QRA successful? How does following the cynefin framework help us in understanding their work better?
	QRA (90 min)	15 min	Work on the activity and look at the different examples in cynefin framework	Discuss in group if needed	
		5 min	Watch video 1 and reflect		
	Resilience building (15 min)	5 min + 5 min	Work on the activity for cynefin framework understanding	Discuss solutions in your group	
		25 min + 20 min	Read through the assignment	Discuss understanding of the assignment - preferably by downloading the handout	Work on task 1 in the class - collect the asnwers - potentially use something like Speakup room to share the answers from everyone
		20 min		Discuss task 2 in group and fill up group wise charts of cynefin framework	Provide printouts of A3 where students can add their solutions
	Assignment (group) (90 min)	25 min			Work on task 3 in the class - collect the asnwers - potentially use something like Speakup room to share the answers from everyone