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The Impact of Systems Thinking Education on Engineering Students' Approach to Real-World Challenges

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1 Abstract

This paper explores the impact of systems thinking education on engineering students by evaluating their ability to apply systems principles to complex real-world problems. A three-year longitudinal study was conducted, examining how students integrated social, environmental, and technical considerations when analyzing a case study on Jordan's water scarcity issue. Utilizing Barry Richmond's Systems Thinking framework and opportunity identification theory, the study assessed students' abilities through 14 semi-structured, hour-long interviews. Participants described their approach to analyzing systemic interdependencies and identifying potential opportunities for intervention.

Thematic analysis of the interviews revealed opportunities categorized into three areas: New Products and Technologies, New or Improved Services, and Policy and Government Changes. Findings indicated that students predominantly identified opportunities within Policy and Government Changes, emphasizing regulatory reforms, governance adjustments, and international cooperation as essential for addressing systemic challenges. Although technological innovations were frequently proposed, these were often contextualized within broader systemic or policy-oriented frameworks.

These results underscore the effectiveness of systems thinking education in fostering a holistic understanding among engineering students, preparing them to address multifaceted societal issues beyond traditional technical boundaries. The study highlights the critical role of interdisciplinary collaboration and systemic awareness, proposing systems thinking as a powerful pedagogical approach for educating engineers equipped to navigate and tackle complex global challenges.

2 Background

2.1 Systems Thinking Teaching in Education

Systems Thinking is an approach that emphasizes understanding complex, interconnected systems. This methodology equips learners with the skills to analyze interdependencies, feedback loops, and emergent behaviors, providing tools to navigate multifaceted challenges [1]. As society increasingly confronts wicked problems—those with no definitive solutions and multiple interdependent variables—the need for Systems Thinking in education has become paramount. Educators and researchers argue that traditional reductionist methods fail to address the complexity of contemporary global challenges, such as climate change, public health crises, and social inequities [2].

The consequences of not embedding Systems Thinking in education can be illustrated through a variety of failed engineering cases with various components. The Flint water crisis is a prime example that arose from a failure to consider the systemic implications of switching the city's water source. Decision-makers focused narrowly on cost savings, neglecting the broader interplay between infrastructure, public health, and governance. The result was a cascading series of failures that led to widespread lead contamination and long-term health consequences for Flint residents [3]. Such failures underscore the importance of equipping students with the tools to think systemically, enabling them to anticipate and address the interconnected aspects of complex problems.

In recent years, Systems Thinking is widely acknowledged as a crucial tool for addressing the complexities of modern challenges, enabling individuals and communities to navigate intricate problem-solving and decision-making processes[4]. The key educational benefits of Systems Thinking include heightened critical thinking, the ability to analyze socio-technical systems, and an aptitude for interdisciplinary collaboration. This pedagogical framework shifts the focus from individual components to the holistic interplay of system elements, fostering interdisciplinary learning and integrative problem-solving skills [5].

Despite its proven benefits, Systems Thinking remains underrepresented in curricula [6]. One of the key barriers is the lack of resources and training for educators to implement this approach effectively. Several institutions and initiatives, however, have made strides in addressing this gap. The Map the System Competition, for instance, has highlighted the role of Systems Thinking in understanding social and environmental problems, showcasing how students can apply these concepts to real-world issues [7]. Research further underscores the importance of integrating Systems Thinking into education to prepare future leaders capable of addressing the interconnected challenges of the 21st century [8].

2.2 Systems Thinking Education in Engineering

Engineering education is uniquely positioned to benefit from Systems Thinking due to the inherently interdisciplinary and complex nature of engineering challenges. Traditional engineering curricula often emphasize technical proficiency and reductionist problem-solving techniques, which can overlook the broader socio-technical context of engineering solutions [9]. Systems Thinking provides a critical framework to bridge this gap, enabling engineers to design solutions that account for social, environmental, and technical dimensions.

As highlighted earlier in Section 2.1, real-world failures like the Flint water crisis illustrate the consequences of engineering decisions made without systemic awareness. An engineering curriculum infused with Systems Thinking principles might have equipped professionals with the skills to foresee the cascading effects of infrastructure changes. For instance, a deeper understanding of socio-technical interfaces could have led to better risk assessment and stakeholder communication, potentially averting the crisis altogether.

The integration of Systems Thinking into engineering education has gained traction in recent years, particularly in response to calls for curricular reforms aimed at addressing global challenges [10]. Courses like TEP 448 at the University of Toronto serve as an example of this integration and are discussed in more detail in Section 2.3. [11].

One widely used model to support conceptual learning in Systems Thinking is Barry Richmond's Systems Thinking Framework, which outlines several key thinking skills such as dynamic thinking, system-as-cause thinking, forest thinking, and operational thinking. Richmond's framework helps structure students' learning progression and provides language for analyzing how learners move from linear to systemic reasoning [12]. This framework is used in this study as the conceptual foundation for evaluating systems competencies in engineering students.

Research also highlights that exposing engineering students to Systems Thinking not only enhances their ability to address complex problems but also prepares them for leadership roles in diverse professional settings. For instance, studies have demonstrated that engineering students trained in Systems Thinking exhibit improved problem-framing abilities, heightened awareness of ethical considerations, and a greater capacity for innovative solution development [13]. These benefits, introduced in Section 2.1, provide the foundational rationale for integrating Systems Thinking into engineering curricula.

2.3 Systems Thinking Course At University of Toronto

TEP448, Using System Mapping to Tackle Complex Social and Environmental Problems, builds upon the foundational ideas introduced in the background sections, specifically the integration of Systems Thinking into education and its transformative potential within engineering. The course is designed to move beyond traditional, reductionist engineering practices by introducing students to system mapping—a Systems Thinking tool widely used in public health, environmental policy, and urban planning—to address wicked problems with technical, social, and environmental dimensions.

This course complements the broader theme of embedding Systems Thinking into engineering education by preparing students to navigate complex, interdisciplinary problems. It reinforces the ideas from the prior sections by providing practical, hands-on experiences where students collaborate to develop system maps that emphasize problem definition over solution development. This aligns with the critical need outlined earlier: to equip engineers with the ability to incorporate socio-technical and environmental dimensions into their analyses.

Key Features of TEP448:

- **Interdisciplinary Approach**: Students explore fields outside engineering—such as public policy, sociology, and law—to develop a nuanced understanding of multifaceted challenges. This reflects the pedagogical shift discussed in Section 2.2, which advocates for interdisciplinary collaboration to prepare engineers for leadership roles in addressing global challenges.

- **Focus on Problem Definition**: The course prioritizes defining complex problems rather than immediately seeking solutions. By critically analyzing existing solutions against their systems maps, students strengthen their problem-framing and critical-thinking abilities, mirroring the learning outcomes identified as essential in Systems Thinking education.
- **Hands-On Learning**: Guest lectures, interactive tutorials, and assignments scaffold learning through iterative exploration, allowing students to internalize Systems Thinking principles and apply them to real-world scenarios. This experiential learning approach aligns with engineering education best practices [14]
- **Alignment with Broader Initiatives**: The final project's compatibility with the *Map the System* competition further situates the course within the global movement advocating for Systems Thinking in education, as discussed in Section 2.1.

The course stands as a practical application of the theories and frameworks introduced earlier in the document, bridging academic insights with real-world applications. By incorporating system mapping and interdisciplinary learning, TEP448 not only deepens students' understanding of Systems Thinking but also equips them with tangible tools to address the socio-technical challenges of the 21st century.

3 Study Details

This study employed a mixed-methods research design to evaluate how engineering students develop Systems Thinking competencies through their engagement with the TEP448 course. Drawing on Creswell and Plano Clark's explanatory sequential design [15], the methodology was structured in two phases: an initial survey instrument to assess changes in students' understanding over the course duration, followed by a qualitative exploration through semi-structured interviews to gain deeper insight into the nature and application of those changes. This approach enabled both the breadth of participation across three academic years and a nuanced examination of individual experiences in applying Systems Thinking concepts to entrepreneurial contexts.

The survey was administered in both the second and final weeks of the course across the 2022, 2023, and 2024 cohorts. It included questions adapted from the validated Engineering Entrepreneurship Survey [16] as well as custom-developed questions focused on the students' perceived confidence and understanding of specific Systems Thinking tools, including causal loop diagrams, iceberg models, and system archetypes. These instruments were aligned with Barry Richmond's Systems Thinking framework to capture students' conceptual grasp and their confidence in applying systems tools to real-world challenges. The survey was pilot tested with graduate students and refined for clarity, accessibility, and alignment with course outcomes.

The survey respondents were undergraduate engineering students from a diverse range of participants from multiple disciplines, including Civil, Mechanical, Electrical, Computer, and Biomedical Engineering. Students also represented different stages of their undergraduate programs, contributing to a heterogeneous learning environment well-suited to the course's emphasis on interdisciplinary teamwork and systems-level problem solving. Demographic information—such as academic program, year of study, gender, age, and international or domestic status—was collected through the survey to contextualize student experiences and inform subgroup analysis. This diversity of backgrounds supports the study's examination of how Systems Thinking competencies develop across varied engineering domains and student profiles.

Over the three-year span, a total of 54 pre-course and 48 post-course surveys were collected. While a statistical comparison of aggregate pre- and post-survey responses was conducted using paired t-tests on matched items, the results did not yield statistically significant differences. As such, the survey primarily served as a diagnostic instrument to identify broad patterns in students' perceptions, inform the development of follow-up interview protocols, and assess overall readiness for Systems Thinking application.

The follow-up interview extended the scope of the study by exploring additional qualitative aspects of students' learning experiences. This included examining their understanding of Systems Thinking concepts and tools, their ability to apply these tools in their careers or entrepreneurial endeavors, and their intentions to pursue entrepreneurial activities. A critical element of the interview was the application of Systems Thinking principles to a provided case study. This case study required participants to demonstrate how they utilized the concepts learned during the course to analyze and address a complex, real-world problem. By integrating this practical exercise into the interview, the study was able to assess not only students' theoretical understanding but also their ability to translate these concepts into actionable insights.

The follow-up interview consisted of semi-structured interviews with a purposefully selected subset of students. Participants were chosen based on their interest in entrepreneurship, performance in the course, and disciplinary diversity, with care taken to include students across multiple academic years and levels of entrepreneurial inclination. A total of 14 interviews were conducted, with each lasting approximately one hour. These interviews were audio recorded, transcribed verbatim, and conducted in accordance with ethical guidelines approved by the University of Toronto Research Ethics Board (REB 42066). Students who participated in the interviews received a $25 Amazon gift card as compensation for their time and contribution.

The interviews were guided by a protocol grounded in three interrelated theoretical frameworks: Barry Richmond's Systems Thinking Process, the Opportunity Identification and Development Theory [17], and the Keen Entrepreneurial Mindset Framework. Interview questions explored students' understanding and confidence in applying Systems Thinking tools, their team's approach to problem framing and exploration, and their process of identifying entrepreneurial opportunities within both course projects and a standardized business case study. These interviews served as the core qualitative component of the study, enabling the evaluation of students' applied knowledge and the transference of conceptual learning into practice.

Qualitative data were analyzed using NVivo software, employing both inductive and deductive thematic analysis techniques. Open coding was used to identify emergent patterns, which were then organized around the constructs of the guiding frameworks. This methodological structure allowed for a detailed investigation of the learning and application outcomes of the course, while also contextualizing the use of Systems Thinking tools within the students' broader entrepreneurial motivations and disciplinary perspectives.

3.1 Case Study

In this section, participants engage with a case study that illustrates the complexities of addressing water scarcity in Jordan as part of the interview (see Appendix 6). The case highlights Jordan's socio-economic growth juxtaposed against its critical water resource limitations. As one of the world's most water-stressed nations, Jordan faces a daunting challenge: balancing the needs of a growing, urbanizing population with limited water availability. Participants were allowed to conduct further web search if they chose to do so.

The case study details the country's water supply, its reliance on overexploited groundwater, and the compounding pressures of international water agreements and urban agricultural practices. Participants were tasked with analyzing this scenario through the lens of Systems Thinking, identifying interconnections, potential leverage points, and actionable solutions.

The analysis began with an open-ended question: "How would you approach this challenge? Walk me through your thinking." This encouraged participants to share their initial insights and structure their approach. Subsequent prompts guided the discussion, asking participants to reflect on the research tools they would utilize, the critical questions they would pose, and potential areas of opportunity. Finally, they were asked to conceptualize areas of opportunity in this case to understand how they go about the opportunity identification using systems thinking.

This structured questioning framework allowed participants to demonstrate their ability to analyze systemic challenges, use Systems Thinking tools, and propose innovative, actionable solutions. The exercise set the stage for a deeper exploration of participants' ability to connect theoretical knowledge to practical, real-world problems.

4 Analysis

The analysis of the data collected from the interviews sought to identify key trends and insights related to students' application of Systems Thinking to complex problems. The primary goal was to assess how effectively students integrated Systems Thinking principles into their understanding of the Jordan water crisis and, more broadly, to evaluate their capacity for identifying viable opportunities for systemic solutions.

Additionally, the interviews allowed for a deeper exploration of how students applied the tools they learned in the course, such as causal loop diagrams, actor maps, and root cause analysis. By analyzing the case study responses, we were able to gauge how students recognized and tackled the interconnectedness of the technical, social, and environmental factors at play. The case study analysis provided a practical demonstration of their ability to frame a complex problem, identify relevant stakeholders, and propose systemic solutions.

The coding of interview transcripts revealed three broad categories of opportunities identified by students: New Products and Technologies, New or

Improved Services, and Policy and Government Changes. These categories were consistent with Systems Thinking's focus on addressing interdependencies and feedback loops within complex systems. Most responses pointed to policy-oriented solutions, including regulatory reforms, governance restructuring, and the development of new public-private partnerships as necessary components of tackling the water crisis. A smaller proportion of students proposed new technological innovations or service-based solutions, though these suggestions often included a component of systemic change or policy overhaul to maximize their potential impact.

The analysis also highlighted the importance of interdisciplinary collaboration in identifying these opportunities. Many students suggested that addressing the water scarcity issue in Jordan would require cross-sector cooperation between engineers, policymakers, sociologists, and environmental experts. This emphasis on collaboration reflects a core tenet of Systems Thinking, which stresses the importance of understanding and integrating multiple perspectives to solve complex, multifaceted problems.

Furthermore, the thematic coding suggested that Systems Thinking supported students in expanding their approaches to problem-solving. In several instances, students moved beyond narrowly technical responses and began to consider broader systemic factors contributing to the challenges they analyzed. This shift, consistent with the benefits described in the Background, points to a growing Systems Thinking mindset among students.

In summary, the data analysis revealed that Systems Thinking education significantly influenced students' ability to approach complex real-world issues with a more holistic and interdisciplinary mindset. The integration of multiple systems perspectives, combined with a focus on policy and societal implications, suggests that students are equipped to address not only the technical dimensions of complex problems but also the social and environmental challenges that underlie them. The following sections will further explore some details on the type and number of each opportunity, followed by the implications of these findings for engineering education.

4.1 New Products and Technologies

In the context of the case study, this category highlights opportunities where students identified the potential for new products or technological innovations to address key challenges within the system. Through their analysis, students explored how advancements in technology or the introduction of novel tools could enhance system efficiency and address specific issues. The evaluation of the case study prompted students to critically assess how emerging technologies might bridge gaps and improve the overall functionality of the system. A variety of products and technologies were proposed, each varying in complexity, scope, and level of detail. Some solutions targeted individuals within the system, while others aimed at broader interventions with the potential to impact entire populations. For instance, some students suggested the development of advanced irrigation systems to support national agriculture, benefiting farmers through government distribution. Conversely, others proposed localized solutions, such as optimized vertical gardens, enabling individuals to grow their own food. The depth of these proposed opportunities varied, with some students offering brief outlines, while others presented detailed strategies for implementation, drawing on examples from other regions. This variation can be attributed to the differing levels of students' familiarity with the subject matter and the limited time available for independent research on the case study.

4.2 New or Improved Services

This category includes opportunities related to the provision or enhancement of services identified through students' analysis of the case study. Students explored areas where new services could be introduced, or existing services improved to better meet stakeholder needs in the context of the water scarcity issue in Jordan. These opportunities often focused on making services more accessible, efficient, or more aligned with the social and environmental challenges posed by the water crisis. While most students proposed technical solutions or systemic changes, a small number recognized the potential for service-based solutions to contribute to system improvement. However, only two students identified specific new or improved services as potential opportunities, which may stem from the limited prior knowledge on the topic and the lack of preparation around the topic of the case study. The complexity of the water shortage problem likely influenced this result, as students tended to view it as requiring large-scale systemic change, rather than solutions based on service provision alone. Furthermore, the service proposals were typically framed in the context of cooperation with other stakeholders, including the government, rather than as standalone ideas.

4.3 Policy and Government Enhancements

This category focuses on opportunities for policy changes or government interventions aimed at addressing the challenges presented in the case study. Students identified regulatory and policy gaps that hindered the effectiveness of the current system and proposed areas where government action could drive improvements. The analysis encouraged students to think about how policy changes or new government initiatives could address broader social and environmental challenges, emphasizing the importance of systemic thinking and interdisciplinary collaboration in governance. The policy-related proposals varied significantly in terms of complexity and implementation. Some recommendations were straightforward and short-term, such as a temporary 30-day water usage restriction, which could provide immediate relief but may not resolve the long-term issue of water scarcity. In contrast, other suggestions were more elaborate, including skill transition programs designed to shift Jordan's agricultural workforce to other sectors. These programs envisioned a long-term transformation of the country from an agriculturally dependent economy to one based on manufacturing, reflecting a more comprehensive approach to systemic change. Additionally, several proposals centered on international collaboration, suggesting that the Jordanian government pursue new partnerships with neighboring countries to access shared water resources. These recommendations demonstrated students' ability to think beyond technical engineering solutions, recognizing the critical role of policy and international cooperation in tackling large-scale, complex problems like water scarcity.

5 Limitations

While this study provides valuable insights into the impact of Systems Thinking education on engineering students' ability to address complex socio-technical challenges, several limitations should be noted.

First, the number of participants involved in the follow-up interviews was limited to 14 students. While this allowed for in-depth exploration of individual experiences, the small sample size may constrain the generalizability of findings across broader engineering populations or institutional contexts.

Second, the case study component of the interviews, which asked students to apply Systems Thinking tools to Jordan's water scarcity crisis, was introduced with limited preparation. Participants were not given advance access to the full case materials or the opportunity to conduct extensive background research prior to the interview. As a result, their analyses were based largely on initial impressions and prior course knowledge, which may have constrained the depth and specificity of their proposed solutions.

Third, the time allocated for participants to explore the case and generate systemic insights during the interview was relatively brief. Given the complexity of the scenario, additional time could have allowed for more thorough investigation of underlying factors and more robust application of Systems Thinking tools.

Finally, while the case study presented a realistic and data-informed scenario, it remained a constructed exercise. As such, students' responses may not fully reflect how they would act in real-world engineering contexts where additional constraints—such as time pressures, stakeholder dynamics, and incomplete information—play a more prominent role. The transferability of insights from this hypothetical case to actual practice should, therefore be interpreted with caution.

These limitations point to areas for future research, including expanding participant samples, incorporating more comprehensive case preparation, and exploring real-world applications of Systems Thinking in professional or co-op settings.

6 Conclusion

This study suggests that Systems Thinking education has the potential to enhance engineering students' abilities to better understand and begin addressing complex, socio-technical challenges. Students participating in the TEP448 course applied Systems Thinking principles—such as feedback loops, leverage points, and stakeholder analysis—to a case study on Jordan's water scarcity. This application offered valuable insights into how students conceptualize problems, identify opportunities, and propose systemic interventions.

Rather than focusing solely on technological fixes, many students proposed policy-oriented and interdisciplinary solutions—indicating a shift toward broader systems awareness. Notably, the majority of students identified policy and governance enhancements as promising interventions, emphasizing long-term change through regulation, international cooperation, and workforce transition strategies. These findings suggest that students are learning to frame problems beyond narrow technical scopes.

Pedagogically, these outcomes point to the value of embedding experiential and interdisciplinary Systems Thinking modules into engineering curricula. Tools such as causal loop diagrams and system mapping encouraged students to navigate real-world complexity—skills not always emphasized in conventional engineering coursework. Moreover, the TEP448 course's alignment with initiatives like the Map the System competition shows the broader relevance of such training.

Importantly, this study offers three tentative insights for engineering education:

- Systems Thinking tools can support opportunity identification across technical, service-based, and policy domains.
- Students may begin to adopt a mindset that values holistic, collaborative approaches over isolated technical solutions.
- Systems Thinking may help cultivate entrepreneurial and leadership capabilities, particularly in contexts involving ambiguity and diverse stakeholders.

Future research could explore how these capacities translate into professional settings, particularly within co-op or industry placements, and how curricula might further scaffold the development of Systems Thinking competencies over time.By helping students think more systemically, institutions may better prepare them to design not only technologies but also the systems in which those technologies function. Overall, these findings point to a growing need for pedagogical approaches in engineering that foster systems literacy as an essential 21st-century competency.

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Appendix

Water Shortage in Jordan Jordan is a country in the Middle East that is classified as an "upper middle income" country by the World Bank. The country has a stable and growing economy, and a number of free trade agreements with other countries all over the world. The developmental standard, and the standard of living, are high in a global comparison.

But Jordan's climate is dry, especially in the eastern parts of the country. It is unclear whether there will be enough water to support the 6.5 million inhabitants in the future. Jordan's population is growing at a rate of 2.7% a year and is increasingly urbanized. The United Nations Development Programme (UNDP) expects the percentage of Jordanians living in urban areas to reach 80% by 2015. Urbanization diverts water away from agriculture into built-up areas for drinking water supply and domestic uses. Jordan is one of the world's most vulnerable countries in terms of water shortage.

In 2007, the annual water demand was estimated to be 1505 billion cubic meters. This number is expected to further increase and reach 1635 billion cubic meters in 2020. Today's water resources are estimated to amount to 665 billion cubic meters annually. The difference between assets and demands is currently bridged by over-exploiting ground water resources.

Almost three-quarters of Jordan's population lives in cities and towns, and in these urban centers there is barely enough water to drink, let alone enough for agriculture. The Ministry of Water and Irrigation estimates that the amount of water available to everyone is less than 200 cubic meters per year. The World Health Organization (WHO) estimates that below 1 000 cubic meters per person, water scarcity can impede economic development and harm human health.

Despite this, a survey by the Jordanian Department of Statistics, with support from the International Development Research Centre (IDRC), estimated that some 50 000 households in the capital city of Amman — or about one in six — practice urban agriculture. City gardeners grow olives, fruit, vegetables, and herbs or keep livestock on plots that average about nine square metres. City gardens totaled 648 hectares, even though only 25% of available space was under cultivation.

The Department estimated the annual total value of the food grown at US$3.5 million, or about $70 per household — not an insignificant amount in a country where the average monthly income is about US $130, and much less than that for the poorest families. However, most of these gardens were irrigated with fresh water from the public distribution system. This at the same time nearly one-third of all households suffered from water scarcity, and many complained of the high price of water.

Apart from these natural limits, water supply is also restricted by an agreement among the countries that surround the Jordan valley: Jordan, Israel, Lebanon, and Syria. According to the “Jordan Unified Water Plan”, which was signed in 1955, these countries have specific water allocations that they are allowed to withdraw from the streams in the valley.