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Assessing Systems Thinking Skills in Engineering Education: Addressing Implementation Challenges and Unintended Consequences in Ill-structured Problems

Dr. John Mendoza-Garcia, University of Florida

John Mendoza Garcia is an Instructional Associate Professor at the Department of Engineering Education in the Herbert Wertheim College of Engineering at the University of Florida. He received his Ph.D. in Engineering Education at Purdue University, and he has a Master's and a Bachelor's in Systems and Computing Engineering from Universidad de Los Andes, in Colombia, and Universidad Nacional de Colombia respectively. He teaches and investigates the development of professional skills such as problem-solving, systems thinking, and design thinking. He worked in Industry before transitioning to academia.

Dr. Andrea Goncher-Sevilla, University of Florida

Andrea Goncher is an Instructional Assistant Professor in Engineering Education at the University of Florida. She earned her PhD in Engineering Education from Virginia Tech and focuses on teaching and learning projects in human centered design and humanitarian engineering.

Dr. Mengyu Li, University of Florida

Mengyu Li is an Instructional Assistant Professor in the Department of Industrial and Systems Engineering (ISE) at the University of Florida (UF). She teaches numerous undergraduate and graduate level ISE courses, including: Supply Chain Management, Senio

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ABSTRACT

Systems engineering involves designing and managing complex systems that interact with human, environmental, and technological factors. Addressing implementation challenges early ensures systems are both theoretically sound and practical. This proactive approach mitigates risks, optimizes resources, and meets intended standards. However, even well-intended decisions can lead to unintended consequences due to the system's complexity. Training students to anticipate these outcomes prepares them to be responsible and effective engineers.

In our study, first-year engineering students completed a scenario-based assessment (Grohs et al., 2018) on systems thinking and problem-solving. Responses were evaluated based on their ability to identify implementation challenges and unintended consequences, particularly their interactions and long-term impacts.

All students identified at least one short-term technical or contextual challenge, but many struggled with recognizing complex interactions and long-term consequences. Similarly, most could identify isolated unintended consequences but overlooked how these factors interconnect.

Findings suggest that while students recognize individual challenges, they may lack a deeper understanding of systemic interactions. This underscores the need for educational strategies that enhance systems thinking, emphasizing interconnectedness and long-term decision impacts. Our results inform approaches to better develop these critical skills in engineering students.

1. INTRODUCTION

Systems engineering is a multidisciplinary field focused on designing and managing complex systems that operate at the intersection of human, environmental, and technological factors. Systems engineers play a critical role in ensuring these systems achieve their intended purpose efficiently and effectively, often under constrained resources and within dynamic environments. This complexity necessitates a comprehensive approach to identifying and addressing potential implementation challenges during the early stages of system design. However, the implementation of complex systems presents a unique set of challenges, requiring careful navigation through both technical intricacies and contextual factors. In the short term, systems engineers often grapple with technical obstacles such as integration issues, scalability concerns, and insufficient data validation [1]. These hurdles can disrupt project timelines and lead to unforeseen costs, particularly when technical risks are underestimated or poorly managed. Long-term challenges are equally significant but often more intricate, involving the need for sustainable maintenance and adaptability of systems in the face of evolving requirements. They tend to extend beyond the technical domain, involving contextual factors like shifting economic conditions, evolving political landscapes, environmental regulations, and social acceptance [2]. From a technical standpoint, systems engineers must ensure robust system interoperability and sustainability. For instance, achieving seamless integration across diverse subsystems requires rigorous testing and iterative refinement [3]. Meanwhile, contextual challenges often demand systems engineers to balance technical goals with broader societal impacts. Economic fluctuations can affect resource allocation, while political instability may introduce regulatory uncertainties that impede system deployment [4]. Environmental considerations, such as compliance with sustainability standards, further compound the complexity of implementation. Social factors, such as public perception and user adoption, can also dictate the ultimate success or failure of a system. Understanding these multi-faceted challenges is crucial for systems engineers to develop effective strategies for both short-term problem-solving and long-term system resilience. By adopting a holistic approach that integrates technical expertise with an awareness of contextual dynamics, systems engineers can enhance their capacity to deliver systems that are functional, sustainable, and adaptable to changing conditions.

Despite meticulous planning and advanced methodologies, the implementation of complex systems often gives rise to unintended consequences. These unexpected outcomes can stem from the inherent complexity of the system itself, unforeseen interactions within its components, or external contextual factors such as economic, social, political, and environmental influences. These issues often arise from interactions between system components and their broader context, leading to cascading effects or unintended behaviors that can undermine system objectives. For example, the rollout of a smart grid system designed to enhance energy efficiency may inadvertently lead to privacy concerns or cyber vulnerabilities due to increased digital connectivity [5]. Similarly, implementing automated decision-making systems in public policy or healthcare can introduce biases that disproportionately affect specific groups, exacerbating social inequities [6]. The introduction of automation in manufacturing can enhance efficiency but may also lead to significant job displacement, creating social and political challenges [7]. These challenges highlight the need for systems engineers to anticipate and address unintended consequences during the design and implementation phases. However, the dynamic nature of complex systems makes it difficult to predict all potential outcomes, as interactions between technical and contextual factors often lead to emergent behaviors. By considering how technical designs interact with contextual factors over time, engineers can improve system resilience and sustainability while avoiding negative downstream effects. For instance, integrating stakeholder input early in the design process and continuously evaluating feedback loops can help identify potential unintended outcomes before they materialize [8].

It is essential to educate and equip engineering students with the skills to navigate the complexities of implementation while ensuring solutions achieve intended outcomes without compromising broader system stability. This study engages first-year engineering students in scenario-based assignments focused on implementation. It investigates their ability to identify and consider both short- and long-term challenges, emphasizing the interaction between technical complexities and the broader economic, political, environmental, and social contexts in which systems engineers operate. Additionally, this study assesses participants' effectiveness in devising strategies to identify and address potential unintended consequences when implementing complex system solutions. The research findings presented in this paper will inform future efforts to design impactful teaching strategies that foster these critical skills and enhance systems thinking abilities among engineering students.

2. METHODS

2.1 Context

Students in an introductory engineering design course completed a systems thinking activity as part of an individual assignment. The course emphasizes engineering design, incorporating human-centered processes and stakeholder input to develop functional prototypes while covering topics such as solid modeling, programming, sensors, actuators, and 3D printing. Open to all engineering majors, it requires no prerequisites and is typically taken in the first year. For this study, data was collected from 21 engineering students who agreed to participate in the study. Participants represented diverse engineering disciplines, and 36% identified as women, 64% as men, and 0% as non-binary. All data collection followed institutional IRB protocols.

2.2 Systems Thinking Assessment Tool

The problem scenario and accompanying rubric assessed systems thinking competencies in contexts extending beyond self-reported attitudes and behaviors. The problem scenario is a hypothetical vignette that requires students to evaluate multiple aspects within an ill-structured problem context. This scenario includes information that potentially encompasses engineering and technical skills, economic feasibility, ethical considerations, and cultural sensitivity, all of which should be taken into account when analyzing potential solutions [9].

> "The Village of Abeesee has about 50,000 people. Its harsh winters and remote location make heating a living space very expensive. The rising price of fossil fuels has been reflected in the heating expenses of Yakutia residents. In fact, many residents are unable to afford heat for the entire winter (5 months). A Northeastern Federal University study shows that 38% of village residents have gone without heat for at least 30 winter days in the last 24 months. Last year, 27 Yakutia deaths were attributed to unheated homes. Most died from hypothermia/exposure (21), and the remainder died in fires or from carbon monoxide poisoning that resulted from improper use of alternative heat sources (e.g., burning trash in an unventilated space)."

2.3 Data Collection

For data collection, the researchers changed the name of the hypothetical village, "Abeesee" to "Yakutia" to reflect a more realistic context. The text provided to students for the activity is, "*The region described in the scenario is real and its community members experience very harsh winters, however the specific details of the scenario are fictional for the purposes of this assignment."* We utilized the assessment tool rubric to evaluate the student responses through the lens of systems thinking constructs derived from the framework. This framework encompasses three key dimensions: the problem dimension, perspective, and time. The interaction of constructs within each dimension facilitated an analysis of students' perspectives and competencies in considering multiple interactive constructs [9].

To understand and assess engineering students' ability to implement solutions and anticipate potential unintended consequences, our research analyzes responses to prompts 7 and 8 explicitly, as they are directly relevant to our focus of this study.

Prompt 7: Implementation Challenges: Without specifically changing your plan (participants first wrote a plan on how they will address the Yakutia situation), reflect on it. What challenges do you see to implementing your plan? What are the limitations of your approach?

Prompt 8: Unintended Consequences: Please describe any unintended consequences that you think might result from this plan.

Figure 1 presents the rubric developed by Grohs et al. [9] for evaluating students' responses regarding the implementation challenges of their plans.

Implementation Challenges *Prompt 7*	**0** No response was provided, or response did not identify any potential implementation challenges **1** The response identified potential simple, ***short-term*** implementation challenges ***focused on one aspect: technical*** or ***contextual*** (economic, political, environmental, social, time, etc) **2** The response identified potential implementation challenges that are: 1. ***focused on one aspect*** and ***long-term***; or 2. ***focused on one aspect*** and consider both ***short- and long-term*** challenges; or 3. consider both ***technical*** and ***contextual aspects*** and ***short-term*** **3** The response identified several potential challenges that consider ***both technical and contextual aspects*** and the possible ***interaction*** between ***aspects***; response recognized possible barriers due to trade-offs between ***short-*** and ***long-term*** plans

Figure 1 - Rubrics provided by Grohs et al. [9] to evaluate participants' answers for prompt 7 related to Implementation Challenges.

When evaluating the participants' responses for unintended consequences, we focused on their answers to prompt 8 and revisited their responses to prompt 7 with a fresh perspective to gather additional insights for rating. Figure 2 shows the rubrics provided by Grohs et al. [9]:

Unintended Consequences *Prompts 7 and 8*	**0** No reponse was provided, or response did not show potential unintended consequences **1** The response identified potential unintended consequences that cover one or more ***aspects: technical*** and/or ***contextual*** (economic, political, environmental, social, time, etc) but did not consider ***interaction*** of different ***aspects*** and issues **2** The response identified several potential unintended consequences. Responses considered/implied issue ***interaction*** of several ***aspects***, but there is notable focus on a ***single aspect*** **3** The response identified several potential unintended consequences. Responses considered and discussed issue ***interaction*** between ***aspects*** and considered both ***short- and long-term*** consequences

Figure 2 - Rubrics provided by Grohs et al. [9] to evaluate participants' answers for prompts 7 and 8 related to unintended consequences.

3. RESULTS

3.1 Data Analysis

Twenty-one students consented to join this study. Each participant's response was independently assessed by three raters using Grohs's systems thinking assessment tool [9], and the scores were subsequently compiled. For instance, the following is Participant 20's response to Prompt 7, where the three raters did not completely agree:

> *"One challenge is getting the government to agree to helping this village. It may not help at all. Another challenge is figuring out who gets the $1,000 grants. One limitation is that only 50 people will get the grant."*

The three raters provided the following scores for this answer, as shown in Table 1.

	Prompt 7: Implementation Challenges					
	Rater	***Notes by rater 1***	***Rater***	***Notes by rater 2***	***Rater***	***Notes by rater 3***
Student ID #	Rater 1		Rater 2		Rater 3	
P-20	3	Considered both technical and contextual aspects – long-term and short-term challenges.	3	No comments	2.3	Two aspects, but both can be considered short-term

Table 1 - Rating of participants' answers for Participant 20 for Prompt 7.

For Prompt 8, we present Participant 16's response as an example where the three raters did not fully agree:

> *"Some unintended consequences may include people having a hard time deciding who should get the grants, as well as being able to install new systems but people are still unable to afford the new systems."*

This answer was scored by the raters as shown in Table 2.

	Prompts 7 and 8: Unintended consequences					
	Rater	***Notes by rater 1***	***Rater***	*Notes by rater 2*	***Rater***	***Notes by rater 3***
Student ID #	Rater 1		Rater 2		Rater 3	
P-16	3	Covered two social aspects	2	No comments	2	Contextual and technical aspects – interconnection is not clear.

Table 2 - Rating of participants' answers for Participant 16 for Prompt 8.

To validate these scores, the Weighted Fleiss'Kappa method [10]–[12] was applied. This Statistical approach measures inter-rater reliability and the "seriousness" of discrepancies [11] (p. 608). In this framework, Weighted Kappa (WK) values above 0.75 indicate "excellent agreement beyond chance," while values of 0.4 or below indicate "poor agreement beyond chance." The WK index values for prompts 7 and 8 were 0.52 and 0.65, respectively. Since both values exceed 0.4, it indicates that the raters' agreement is sufficiently strong. For the example provided for prompts 7 and 8, there was no full agreement between the raters. In these cases, we selected as the participant's level the one in which the majority of the raters agreed with the answer's score. For example, for Participant 16, the level selected is 2 because only one of the raters scored this participant with a 3.

3.2 Findings

Prompt 7: Three participants (13.6%) achieved a level 1 score, while fifteen participants (68.2%) scored at level 2, with four (18.2%) at level 2.1, three (13.6%) at level 2.2, and eight (36.4%) at level 2.3. Additionally, four participants (18.2%) achieved a level 3 score. Figure 3 provides a histogram illustrating the distribution of student scores for Prompt 7.

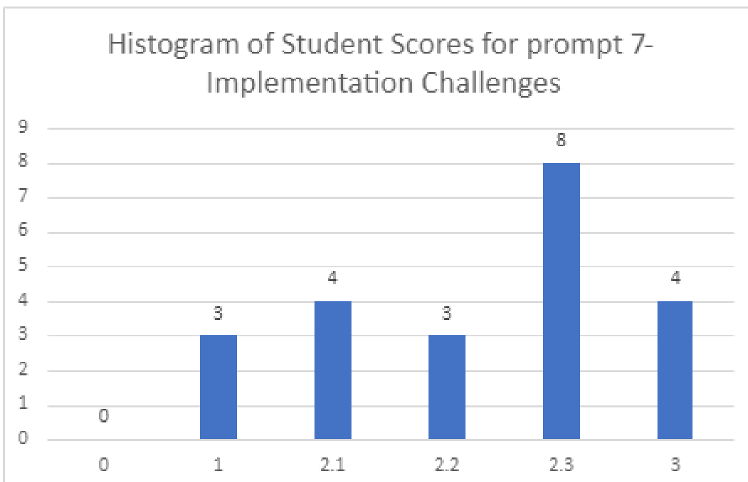

Figure 3 - Distribution of participants' answers on implementation challenges.

Prompt 8: Thirteen participants (61.9%) received a level 1 score for their answers, seven (33.3%) scored at level 2, and one (4.8%) scored at level 3. Figure 4 presents a histogram of the students' responses for Prompt 8.

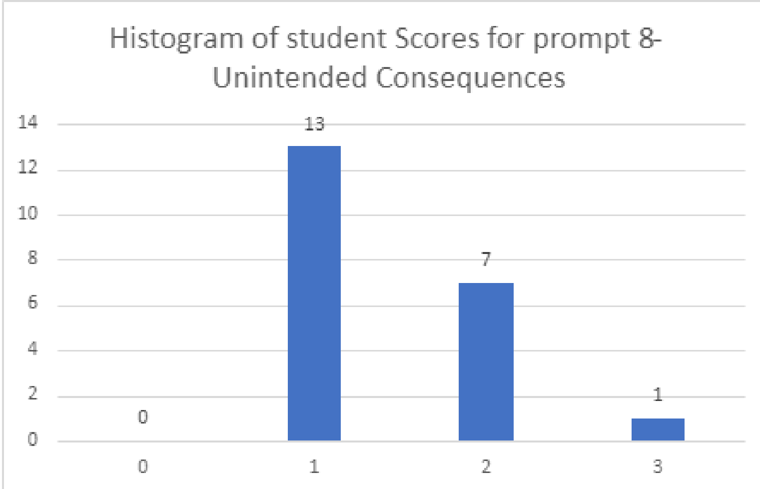

Figure 4 - Distribution of participant's answers related to unintended consequences.

Table 3 presents a comparative overview of the participant responses scores (n = 21).

Level	Prompt 7	Prompt 8
1	3 (13.6%)	13 (61.9%)
2		7 (33.3%)
2.1	4 (18.2%)	
2.2	3 (13.6%)	
2.3	8 (36.4%)	
3	4 (18.2%)	1 (4.8%)

Table 3 - Comparative overview of participant scores for Prompts 7 and 8.

4. DISCUSSION AND IMPLICATIONS

When it came to implementation challenges, all students identified at least one short-term challenge related to either the technical or contextual (economic, political, environmental, social, time, etc.) aspects of the scenario. However, many struggled to recognize the interactions between different constructs at a higher level of complexity and had difficulty considering long-term challenges. Similarly, regarding unintended consequences, most students could identify potential issues related to technical or contextual factors, but they often overlooked the interactions between these various aspects. For Prompt 7, the data shows that most participants' responses were classified at level 2, with 36.4% achieving the highest score within this level. This indicates that these participants discussed two aspects, and the potential short-term implementation challenges they might encounter. However, 45.4% of participants scored at the lower levels, addressing only one aspect and focusing on either the short-term, the long-term, or both without integration. Notably, only 18.2% of participants achieved the highest level, demonstrating an understanding of the interaction between the identified aspects in both the short and long term.

For Prompt 8, most responses regarding potential unintended consequences were classified at level 1. This suggests that most participants did not consider the interactions between two or more identified aspects in their answers. The findings in this study demonstrate that while students can identify short-term challenges and potential unintended consequences in isolation, they may lack the more profound understanding necessary to recognize the complexity of interactions between different aspects of a system. This highlights the need for enhanced educational strategies that emphasize the importance of considering both the interconnectedness of system components and the potential long-term consequences of decisions.

The findings from this study contribute to developing effective teaching strategies to foster systems thinking skills in engineering students. These strategies are essential for preparing students to navigate the complexities of modern engineering challenges, where technical, social, economic, and environmental factors often intersect. Building on these insights, we plan to design innovative teaching components and modules that specifically target areas for improvement identified through participants' current performance. These modules will integrate real-world scenarios and problem-based learning activities, encouraging students to think critically and holistically about interconnected systems.

4.1. Limitations

Responses in a hypothetical scenario may not accurately reflect what individuals would do in real life. The sample population reflects first-year students, who typically have limited professional experience to inform their decisions. Students' answers can also be influenced by their interpretation and understanding of the fictional scenario and its prompts, which can vary significantly among participants. Additionally, our method for collecting responses did not restrict access to external resources, allowing participants to conduct independent online research or consult other sources to inform their answers. Another limitation of this study is the small sample size (n=21), which may have constrained the breadth of the findings and potentially led to incomplete reflections on the challenges or consequences identified by participants.

5. FUTURE DIRECTIONS FOR RESEARCH

Increasing the number of participants in the study would enhance the robustness of the findings, providing more substantial support for their relevance in different contexts. This is particularly important when considering teaching strategies to improve systems thinking among engineering students.

We plan to leverage *Artificial Intelligence* (AI) to create a variety of scenarios that can be adapted based on the course, discipline, and proposed strategies. We also propose that AI can be employed to simulate responses, enabling students to explore the potential long-term consequences of their decisions. Utilizing the teaching materials developed for different scenarios can promote adaptability and sustainability, equipping students with the skills to anticipate unintended consequences and address the long-term impacts of their decisions.

Our previous study [13] suggests that a scaffolded approach can assist students in addressing constraints or limitations when engaging in goal formulation activities. We anticipate similar outcomes for this study, where providing additional guidance (scaffolding information) may enable participants to develop more robust, sustainable, and adaptable solutions. We intend to test this theory in future research.

With that, the curriculum can include scaffolded exercises, collaborative projects, and opportunities to utilize advanced tools such as Artificial Intelligence. Through these efforts, we aim to empower engineering students to approach complex problems with greater insight, confidence, and competence, ultimately shaping a new generation of well-equipped engineers to contribute to innovative and sustainable solutions in their fields. Future studies will test the effectiveness of these teaching strategies and refine them based on continuous feedback and performance evaluations.

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