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Evaluating and Refining Hands-On Systems Thinking and Systems Engineering Activities in Mechanical Engineering Courses

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Abstract

Engineering programs often emphasize technical analysis in the early curriculum, while systems thinking (ST) and systems engineering (SE) concepts are introduced later or treated as specialized topics. As a result, students may have limited opportunities to develop systems-oriented ways of thinking when they first encounter authentic engineering problems. To address this gap, this multi-institutional project integrates and evaluates a set of hands-on activities designed to introduce ST and SE principles in first-year mechanical engineering courses across three universities.

The instructional approach follows a flipped classroom model in which students complete online modules outside of class and engage in structured, in-class activities that reinforce systems concepts through collaboration, discussion, and reflection. This paper focuses on the refinement and evaluation of three one-hour activities: a Product Decomposition exercise in which students analyze subsystems and interfaces within a wind-up toy, a stakeholder role-playing case study based on the 2023 Titan submersible disaster that examines how expertise, bias, and organizational context shape system-level decisions, and a Paper Airplane Design Challenge that emphasizes teamwork, budgeting, iteration, and performance trade-offs. A fourth activity is under development to extend these learning objectives through rapid prototyping and solution-neutral, mission-driven design.

Recent refinements account for differences in classroom settings, resources, and instructional constraints across institutions. Updated instructional materials include clearer prompts, standardized assessments, and embedded reflection questions intended to strengthen alignment between hands-on experiences and targeted ST/SE concepts. To evaluate the effectiveness of these refinements, student survey responses, open-ended feedback, instructor reflections, and emerging assessment artifacts from Fall 2024 through Fall 2025 implementations are analyzed using a mixed-methods approach.

Results indicate that students consistently perceive the activities as engaging and valuable for learning systems concepts, with particularly strong responses to the Product Decomposition activity. Instructor feedback highlights the importance of facilitation, pacing, and scaffolding to support abstraction and systems-level reasoning. Together, these findings inform ongoing refinement of the activities and provide practical guidance for integrating systems thinking and systems engineering concepts into early engineering coursework.

Keywords:

Systems Thinking and Systems Engineering Education, Design-Based Learning, Curriculum and Instructional Design, Assessment and Evaluation Methods, Student Engagement and Motivation

Introduction

Engineering practice increasingly requires engineers to reason about complex systems that integrate technical components with human, organizational, and environmental considerations. Contemporary engineering problems rarely involve isolated components; instead, they are shaped by interacting subsystems, competing stakeholder priorities, and trade-offs that unfold over a system life cycle. Systems thinking (ST) and systems engineering (SE) provide frameworks for navigating this complexity by emphasizing holistic reasoning, integration, and decision-making under uncertainty [1-3]. Despite their relevance, ST and SE concepts are often underrepresented in the early stages of undergraduate engineering curricula, particularly within discipline-specific programs such as mechanical engineering [4], [5]. Introductory engineering courses typically prioritize foundational analysis, tools, and disciplinary identity formation, leaving limited space for students to engage with system-level reasoning. When systems concepts are introduced only in upper-division courses, students may come to view ST and SE as specialized topics rather than as foundational ways of approaching engineering problems.

Prior work in engineering education has argued for earlier exposure to systems-oriented perspectives to help students manage complexity, collaborate across disciplines, and make informed design decisions [6], [7]. Experiential and hands-on learning approaches have been shown to be especially effective for introducing abstract concepts to novice learners, as they allow students to interact directly with physical systems and reflect on their behavior [10]. Activities such as product decomposition, design challenges, and case-based learning make ideas like subsystems, interfaces, system boundaries, and trade-offs more tangible and accessible. Recent studies have demonstrated the feasibility of embedding hands-on ST and SE activities into first-year engineering courses and have reported positive student engagement and instructional value [8], [9]. However, much of this literature focuses on activity development and initial implementation. Fewer studies examine how these activities function across varied classroom contexts, how students perceive their clarity and relevance, or how instructors adapt facilitation strategies in response to logistical and pacing constraints. As a result, instructors seeking to adopt systems-oriented activities often lack evidence-based guidance on how to refine and sustain these interventions over time.

This paper addresses that gap by evaluating and refining a set of hands-on systems thinking and systems engineering activities implemented in first-year mechanical engineering courses across multiple institutions. Rather than introducing new instructional activities, the focus of this work is on examining how established activities are experienced by students and instructors in authentic classroom settings and how multiple sources of evidence can inform iterative improvement. The evaluation draws on student survey data, open-ended feedback, instructor reflections, and emerging assessment artifacts to provide a grounded understanding of activity effectiveness. By emphasizing evaluation and refinement, this work contributes practical insight for educators seeking to integrate ST and SE concepts into introductory engineering coursework. The findings highlight both the instructional value of hands-on systems activities and the design considerations necessary to support consistent learning outcomes, scalable adoption, and meaningful engagement with systems-oriented thinking early in the engineering curriculum.

Related Work and Conceptual Framing

This section situates the present study within prior research on systems thinking and systems engineering education, with particular attention to early curricular integration, hands-on instructional approaches, and case-based learning for socio-technical systems. Together, this literature motivates the activity designs examined in this paper and underscores the need for evaluation-focused work that examines how such activities function in authentic classroom settings.

Systems Thinking and Systems Engineering in Undergraduate Education

As engineering challenges have grown increasingly complex and interconnected, systems thinking and systems engineering have been widely recognized as essential competencies for engineers across disciplines [1-3]. Systems thinking emphasizes holistic reasoning about interactions, boundaries, feedback, and context, while systems engineering provides structured approaches for translating stakeholder needs into integrated solutions across the system life cycle. These perspectives support engineers in navigating uncertainty, managing trade-offs, and coordinating across technical and organizational domains. Despite their importance, ST and SE concepts are often introduced late in undergraduate engineering curricula or confined to specialized courses and programs [4], [5]. In many mechanical engineering programs, systems topics appear primarily in upper-division design or elective courses, limiting students' early exposure to systems-oriented reasoning. This sequencing can reinforce reductionist problem-solving habits and make it more difficult for students to integrate systems perspectives into later design experiences. Prior work has argued that introducing systems-oriented thinking earlier can help students develop more flexible mental models of engineering problems and better prepare them for open-ended, real-world challenges [6], [7].

Hands-On and Experiential Approaches to Systems Education

Hands-on and experiential learning approaches have been shown to be effective for introducing abstract engineering concepts to novice learners, particularly when paired with structured reflection and clear learning objectives [10]. By engaging directly with physical systems, students can observe emergent behavior, identify subsystem interactions, and reason about trade-offs in ways that are difficult to replicate through lecture alone.

Within first-year engineering contexts, activities such as product decomposition and constrained design challenges have been used to support early engagement with systems concepts while maintaining accessibility and low implementation cost [8], [9]. These approaches align with experiential learning theory, which emphasizes learning through concrete experience, reflection, and iteration [10]. Prior publications by the authors documented the development and initial implementation of hands-on ST and SE activities in introductory courses, reporting strong student engagement and instructional feasibility across institutions [8], [9]. However, much of the existing literature emphasizes activity design and classroom deployment rather than systematic evaluation. While student enjoyment and perceived relevance are commonly reported, fewer studies examine how clearly students understand targeted systems concepts, how instructors navigate facilitation and pacing challenges, or how assessment data can inform iterative refinement. This gap motivates the evaluation-centered focus of the present study.

Case-Based and Role-Playing Approaches for Socio-Technical Systems

Case-based learning and role-playing have a long history in engineering education as methods for exploring ethical reasoning, stakeholder perspectives, and decision-making under uncertainty [11]. When applied to systems engineering contexts, these approaches help students move beyond purely technical analyses to consider organizational, social, and ethical dimensions of engineering systems.

Contemporary case studies grounded in real-world events can be particularly effective in engaging students and illustrating the consequences of system-level decisions [11]. Role-playing approaches encourage perspective-taking and reduce hindsight bias by positioning students as stakeholders rather than external analysts. At the same time, prior work has identified instructional challenges associated with these activities, including time management, role clarity, and alignment with learning objectives [9]. These challenges underscore the importance of facilitation design and iterative refinement informed by classroom evidence.

Framing the Present Study

Building on this body of work, the present study examines a set of hands-on systems thinking and systems engineering activities implemented in first-year mechanical engineering courses across multiple institutions. Prior publications established the feasibility and instructional value of these activities [8], [9]. This paper extends that work by shifting the focus from development to evaluation and refinement. Specifically, this study integrates student survey data, open-ended feedback, instructor reflections, and emerging assessment artifacts to examine how these activities function in practice and how they can be improved to better support systems-oriented learning. By centering evaluation rather than novelty, this work contributes practical insight into how hands-on ST and SE activities can be refined to support clearer learning outcomes, more consistent facilitation, and broader adoption across varied instructional contexts.

Activity Design and Instructional Context

This study examines three hands-on activities designed to introduce systems thinking and systems engineering concepts in first-year mechanical engineering courses. The activities were developed and iteratively refined across multiple offerings and institutions, with prior publications documenting their initial design and classroom deployment [8], [9]. The focus here is on how these activities were structured, implemented, and adapted within authentic instructional contexts to support systems-oriented learning at the introductory level.

Instructional Context and Course Settings

The activities were implemented in first-year mechanical engineering courses at three universities. While the courses shared common goals related to introducing engineering practice, design, and professional thinking, instructional contexts varied across institutions. Differences included class size, physical classroom layout, access to instructional assistance, and available time for in-class activities. Rather than attempting to control for these differences, the activities were intentionally designed to be adaptable to a range of instructional settings. All implementations followed a flipped classroom model. Students completed online modules introducing foundational ST and SE concepts prior to class, while in-class time was dedicated to collaborative, activity-based learning. Each activity was designed to fit within a single 50-minute class period and to be facilitated by a course instructor without specialized equipment. This structure supports scalability and lowers barriers to adoption in introductory courses with limited resources [12].

Product Decomposition Activity

The Product Decomposition activity introduces systems concepts through physical disassembly of a wind-up toy. Students work in small teams to identify subsystems, components, and interfaces, and to reason about how energy, motion, and control propagate through the system. The activity emphasizes functional relationships and system boundaries rather than detailed component analysis. Students document their reasoning through sketches, short written prompts, and a system-level representation that captures subsystem interactions.

The instructional goal of this activity is to support abstraction by guiding students from concrete physical artifacts toward higher-level system representations. Reflection prompts ask students to consider alternative decompositions, interactions with the external environment, and the implications of design decisions on overall system behavior. This activity has been shown to be highly engaging and accessible for novice learners while introducing core ST/SE vocabulary and concepts [8].

Submarine Stakeholder Case Study

The Titan Submersible stakeholder case study engages students in systems thinking through structured role-play and facilitated discussion. Students are assigned stakeholder roles, such as engineers, managers, scientists, or regulators, and are asked to evaluate a complex engineering system under uncertainty. The activity emphasizes how expertise, organizational context, incentives, and bias influence system-level decisions.

Rather than focusing on technical failure analysis, the case study foregrounds socio-technical reasoning and ethical considerations. Students are asked to advocate for decisions from their assigned stakeholder perspectives and to participate in structured discussion and voting rounds. This framing encourages perspective-taking and helps students recognize that system outcomes emerge from interactions among technical and non-technical factors [8], [9].

Paper Airplane Design Challenge

The Paper Airplane Design Challenge introduces systems optimization and trade-offs through a fast-paced, team-based design task. Student teams design, build, test, and refine paper airplanes under constraints related to materials, budget, and performance criteria. The activity is structured in stages, with explicit opportunities for iteration, testing, and reflection.

This activity emphasizes system-level decision-making by requiring students to balance competing objectives and to consider how design choices interact across the system. Budgeting and material constraints are used to reinforce trade-offs and resource allocation, while reflection prompts guide students to connect physical performance outcomes to underlying systems concepts. Prior work has shown that this activity effectively supports engagement and systems-oriented reasoning, while also being sensitive to facilitation and logistical considerations [9].

Cross-Activity Design Principles

Across all three activities, several shared design principles guided development and refinement. First, the activities are intentionally time-bounded to fit within a single class period. Second, materials and logistics are kept low-cost and accessible to reduce implementation barriers. Third, each activity includes structured reflection prompts to support sensemaking and explicit connections between hands-on experience and abstract ST/SE concepts. Instructor-facing materials are treated as core instructional artifacts rather than supplemental resources. Activity guides, facilitation notes, and assessment prompts were iteratively refined based on student feedback and instructor observations. This emphasis reflects the recognition that effective systems education depends not only on activity design, but also on how activities are framed, sequenced, and facilitated in the classroom.

Methods

This study employs a mixed-methods approach to evaluate the effectiveness and instructional fit of three hands-on systems thinking and systems engineering activities implemented in first-year mechanical engineering courses. The evaluation is intentionally formative, with the goal of identifying patterns that inform iterative refinement rather than establishing causal relationships or comparing instructional treatments.

Study Design and Evaluation Focus

The evaluation was guided by three complementary questions:

1. How do students perceive the clarity and engagement of the hands-on activities?
2. What insights do open-ended student feedback and instructor reflections provide about activity effectiveness and implementation challenges?
3. How can emerging assessment artifacts support ongoing refinement of activity design and facilitation?

Rather than focusing on individual student learning trajectories, the analysis examines activity-level patterns across implementations. This framing aligns with the instructional design goals of the project and supports evaluation across varied classroom contexts.

Data Sources and Collection

Data were collected across multiple implementations from Fall 2024 through Fall 2025. Three primary data sources were used in the analysis.

Student Surveys

Following each hands-on activity, students completed a brief post-activity survey that included two Likert-scale items assessing perceived clarity and engagement. Responses were recorded on a five-point scale ranging from strongly disagree to strongly agree. An optional open-ended prompt invited students to share additional feedback about the activity. Participation was voluntary and anonymous. Survey responses were aggregated by activity across semesters and course sections.

Instructor Feedback

Instructor feedback was collected through written reflections following activity implementation. Instructors commented on student engagement, clarity of instructions, pacing, alignment with course content, and facilitation challenges. These reflections provide an instructional perspective on activity effectiveness and highlight contextual factors that are not captured through student surveys alone.

Assessment Artifacts

To complement perception-based measures, multiple-choice quizzes were developed to assess student understanding of targeted ST and SE concepts associated with each activity. These quizzes were designed to align with activity learning objectives and to provide a more quantitative indication of conceptual understanding. Quiz data have been collected from implementations at multiple institutions and are currently under analysis. As such, this paper reports survey and qualitative findings, while quiz analysis is described as ongoing work.

Quantitative Analysis of Survey Data

Quantitative analysis focused on descriptive characterization of student perceptions of clarity and engagement. For each activity, response distributions across Likert categories were computed and visualized. Aggregated results are presented in Figure 1, which compares clarity and engagement ratings across activities. Survey data were examined for overall trends and activity-level differences rather than statistical significance. This approach supports interpretation of how activity structure, familiarity, and logistical factors influence student perceptions, while remaining consistent with the formative goals of the evaluation.

Qualitative Analysis of Open-Ended Feedback

Open-ended student responses and instructor reflections were analyzed using inductive thematic analysis. This approach allows themes to emerge from the data rather than imposing predefined categories. Analysis focused on recurring ideas related to engagement, clarity, learning value, facilitation demands, and alignment with systems thinking and systems engineering concepts. The analysis followed an iterative process of familiarization, initial coding, and theme refinement. Generative AI tools were used as an analytic aid to support systematic organization of qualitative responses under clearly defined constraints. These tools assisted with clustering and summarizing recurring patterns but did not generate interpretations beyond those grounded in the written data. Final theme identification and interpretation remained the responsibility of the researchers.

Results

Results are organized by activity to highlight patterns in student perceptions, open-ended feedback, and instructor observations. This structure reflects differences in activity design, familiarity, and implementation context, while also supporting comparison across activities.

Student Perceptions of Clarity and Engagement

Student perceptions of clarity and engagement were measured using post-activity Likert-scale surveys administered following each hands-on activity. Aggregated response distributions across activities are shown in Figure 1, which compares clarity and engagement ratings for the Product Decomposition activity, the Paper Airplane Design Challenge, and the Titan Submersible stakeholder case study.

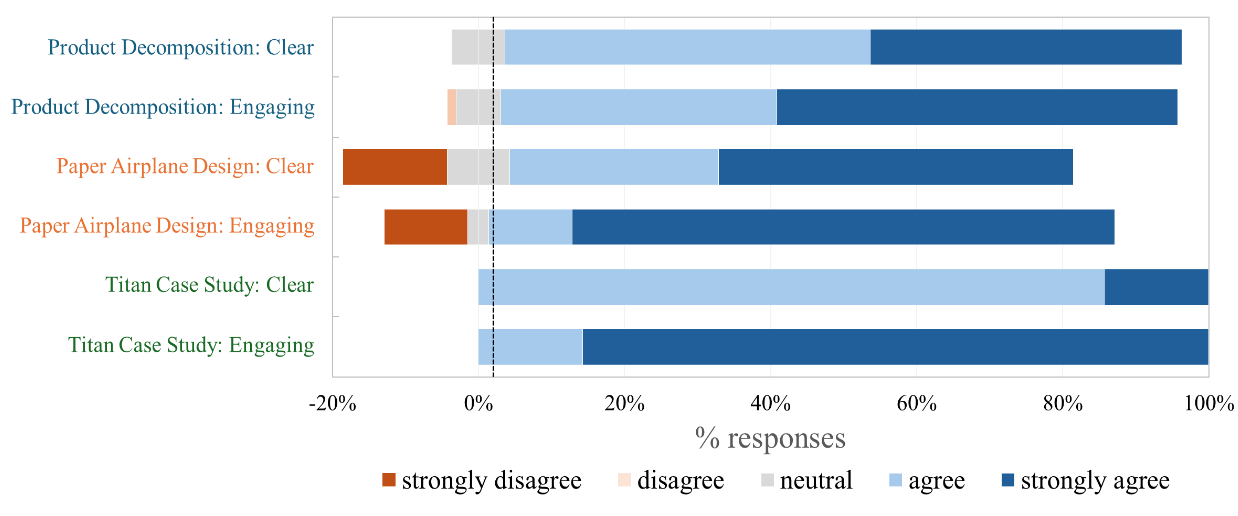

Figure 1. Likert-scale responses to student survey following each "hands-on" activity asking if the activity was clear and engaging

Across all activities, responses skew strongly toward agreement and strong agreement for both clarity and engagement, indicating that students generally perceived the activities as understandable and engaging complements to the systems thinking and systems engineering content introduced in the flipped classroom modules.

Product Decomposition Activity

In the Fall 2025 semester, 82 new student responses were collected for the Product Decomposition activity, making it the activity with the largest response count and the most consistently positive ratings. Only one student selected "disagree" in response to the engagement prompt, while the remaining responses clustered in the agree and strongly agree categories. Compared to the other activities, the Product Decomposition activity received the strongest overall ratings for both clarity and engagement. Open-ended student feedback reinforces these quantitative results. Many comments expressed strong positive sentiment, frequently describing the activity as fun, engaging, well organized, and effective for learning. Students repeatedly emphasized the value of physically disassembling a wind-up toy to understand systems and subsystems, highlighting the tactile and interactive nature of the experience. Many comments explicitly linked enjoyment with learning value, suggesting that the activity supported sensemaking around systems concepts and reinforced material introduced in the online modules [8]. A small subset of students expressed neutral or negative sentiment, primarily related to prior exposure to the same or a very similar activity in another course. In these cases, reduced engagement appeared to stem from familiarity rather than shortcomings in activity design.

Instructors were aware of this risk and noted that reuse of the activity was intentional due to strong alignment with course learning objectives.

Instructor feedback aligned closely with student perceptions. Instructors consistently described the Product Decomposition activity as a refreshing and engaging departure from lecture-based instruction, with many students continuing to discuss the activity outside of class. At the same time, instructors identified recurring challenges related to system-level diagramming. Students frequently interpreted the diagram as a detailed component drawing rather than a functional abstraction, indicating confusion about system boundaries and diagram intent.

Paper Airplane Design Challenge

Thirty-five new survey responses were collected for the Paper Airplane Design Challenge. While overall responses remained positive, this activity exhibited the highest proportion of negative ratings across the three activities, including several "strongly disagree" selections related to clarity and engagement. Despite this, open-ended student feedback was overwhelmingly positive. Nearly all comments emphasized fun, engagement, and interest, with several students describing the activity as one of the most enjoyable assignments of the semester. These responses suggest that students found the activity motivating, even when clarity varied across activities.

Instructor feedback provides context for this divergence between Likert-scale ratings and qualitative sentiment. Instructors reported that the activity was effective in reinforcing systems thinking and systems engineering concepts related to system-level design, iteration, and trade-offs [9]. However, they emphasized that clarity of material rules and logistical support played a significant role in shaping student experience. Sections with clearly defined material constraints and adequate testing space were described as smoother and more engaging, while constrained space or limited instructional assistance introduced challenges related to pacing and fairness.

Submarine Stakeholder Case Study

The Titan Submersible stakeholder case study received seven new survey responses. Although the sample size was small, all responses indicated positive assessments of clarity and engagement. Open-ended feedback was limited but uniformly positive, with students describing the activity as enjoyable and reporting no confusion or frustration.

Instructor feedback indicated that the activity effectively engaged students in stakeholder analysis and ethical reasoning within a complex engineering context. Instructors noted that directing students to focus on stakeholder perspectives, rather than prior knowledge of the real-world incident, helped maintain productive discussion. One instructor incorporated AI-generated images into stakeholder role cards, which increased role immersion and student engagement. Timing was identified as the primary challenge, as some sections felt rushed and limited opportunities for extended discussion.

Emerging Assessment Artifacts

As described in prior project documentation, multiple-choice quizzes were developed to follow each hands-on activity and assess student understanding of targeted systems thinking and systems engineering concepts. These quizzes were designed to provide a quantitative complement to perception-based measures. Quantitative analysis of assessment scores is displayed in Figure 2, showing the average post-activity assessment score for the Product Decomposition, Paper Airplane Design, and Titan Case Study activities.

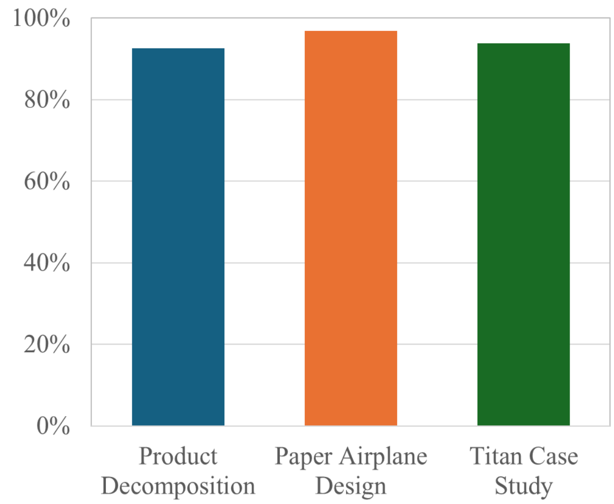

Figure 2. Average student post-activity assessment scores for each activity

Across all activities, responses show high assessment scores, with all three activities' average being above 90%. This suggests that students were able to effectively grasp and apply the targeted systems thinking and systems engineering concepts following each hands-on exercise.

Findings

Synthesis of student survey data, open-ended feedback, and instructor reflections reveals several recurring findings related to engagement, clarity, facilitation, and instructional fit of the hands-on systems thinking and systems engineering activities. These findings reflect patterns observed across activities and implementations rather than isolated outcomes from a single course.

Hands-On Engagement Supports Entry into Systems-Oriented Thinking

Across all activities, students consistently reported high levels of engagement, indicating that hands-on interaction serves as an effective entry point for introducing systems concepts to novice learners. Activities that involved physical interaction with artifacts, such as disassembling a wind-up toy or iteratively testing paper airplanes, were frequently described as fun and motivating. Student comments often linked enjoyment with learning value, suggesting that engagement supported sensemaking rather than distraction. The Product Decomposition activity stood out for both high response volume and strong positive ratings. Students appeared especially receptive to activities that made systems tangible through direct manipulation, reinforcing the value of tactile experiences in early systems education [8].

Engagement and Clarity Do Not Always Co-Occur

Findings also indicate that engagement and perceived clarity are related but distinct dimensions of student experience. While the Paper Airplane Design Challenge generated enthusiastic qualitative feedback, it also exhibited the widest range of Likert-scale ratings for clarity and engagement. This divergence suggests that students may find an activity enjoyable even when its objectives, constraints, or structure are not fully clear.

This pattern highlights the importance of explicit scaffolding and facilitation in hands-on systems activities. Without clear framing and transitions, high-energy activities may obscure intended learning outcomes, particularly for students encountering systems concepts for the first time.

Abstraction and System Boundaries Remain Challenging for Novice Learners

Instructor feedback consistently pointed to challenges related to abstraction and system-level representation, especially during the Product Decomposition activity. While students readily identified components and subsystems, many struggled to articulate functional relationships or to distinguish system-level diagrams from detailed component drawings. These difficulties reflect a broader challenge in early systems education: supporting students in moving from concrete artifacts to abstract representations.

The placement and framing of diagramming tasks emerged as influential factors shaping student interpretation. When system representations were introduced too early, students tended to focus on detailed features rather than higher-level structure, suggesting that sequencing and scaffolding are critical to supporting abstraction.

Facilitation and Logistics Shape Activity Effectiveness

Findings across activities emphasize the role of facilitation, pacing, and classroom logistics in shaping student experience. Discussion-based and iterative activities placed significant demands on instructors to manage time, guide transitions, and support equitable participation. The Titan Submersible stakeholder case study was particularly sensitive to pacing, with limited time occasionally constraining depth of discussion.

Similarly, logistical factors such as material availability, testing space, and instructional assistance influenced the effectiveness of the Paper Airplane Design Challenge. Sections with clear material rules and adequate space were perceived as smoother and more engaging, while constrained environments introduced challenges related to pacing and clarity.

Repetition Influences Perception but Not Instructional Value

A small subset of students expressed neutral or negative perceptions of the Product Decomposition activity due to prior exposure in earlier courses. These responses were associated with reduced novelty rather than dissatisfaction with the activity itself. Instructor awareness of this risk suggests that repetition was a deliberate curricular decision rather than an oversight.

This finding indicates that hands-on systems activities may serve different instructional purposes depending on placement within the curriculum. While novelty may drive engagement in first-year contexts, the same activity can function as a shared reference point for deeper analysis in later courses.

Evidence-Informed Refinement Is Feasible and Productive

Finally, the integration of multiple evidence sources supported targeted, evidence-informed refinement of activity design and facilitation. Student surveys provided insight into perceived clarity and engagement, open-ended feedback revealed how students interpreted activity goals, and instructor reflections surfaced facilitation and logistical challenges. Together, these data sources enabled specific adjustments to prompts, sequencing, and instructional guidance without requiring wholesale redesign.

While analysis of quiz-based assessment data is ongoing, the findings reported here demonstrate that formative evaluation can meaningfully inform refinement of hands-on systems activities in early engineering education.

Implications for Systems Engineering Education

The findings from this study suggest several implications for how systems thinking and systems engineering concepts can be integrated, supported, and sustained within early undergraduate engineering curricula. Rather than positioning ST and SE as advanced or specialized topics, the results indicate that these perspectives can be meaningfully introduced in first-year courses when supported by carefully designed, hands-on instructional activities.

Implications for Early-Curriculum Design

Introducing systems-oriented thinking in the first year supports the development of foundational habits of mind that influence how students approach later coursework. Student responses across activities indicate that novice learners are receptive to systems concepts when they are embedded in tangible, interactive experiences. Activities such as product decomposition, stakeholder role-play, and constrained design challenges provide accessible entry points for engaging with system boundaries, interactions, and trade-offs that might otherwise feel abstract or disconnected from early technical content [8], [9]. At the same time, the findings highlight the importance of deliberate scaffolding. Challenges related to abstraction and system-level representation suggest that early systems instruction must explicitly support transitions between physical artifacts, conceptual models, and higher-level reasoning. Curriculum designers should consider how systems concepts are revisited and reinforced across activities and courses, rather than introduced as isolated experiences.

Implications for Instructional Practice and Faculty Adoption

From an instructional perspective, this work underscores the central role of facilitation in effective systems-oriented learning experiences. Instructor feedback demonstrates that hands-on and discussion-based activities place different demands on instructors than traditional lecture formats, particularly with respect to pacing, role management, and guiding abstraction. Instructor-facing materials such as facilitation notes, timing guidance, and examples of common student challenges emerged as critical supports for consistent implementation. The findings also emphasize the need for flexibility in activity design. Differences in classroom layout, class size, staffing, and access to space influenced how activities were experienced by students. Providing adaptable activity frameworks, rather than rigid scripts, allows instructors to preserve core learning objectives while accommodating local constraints. Explicit documentation of logistical considerations, such as material rules or testing environments, can further reduce barriers to adoption. Table 1 summarizes the identified themes and their relative prevalence across instructor responses.

Table 1: Summary of Instructor Themes and Relative Prevalence

Theme	Description	Relative Prevalence
Engagement as Experiential Driver	Activities described as increasing student interest or motivation relative to lecture-based instruction	Frequent
Instructional Clarity and Task Specification	Comments related to clarity of instructions, roles, and scaffolding	Frequent
Alignment to Course Concepts	Descriptions of how clearly activities connected to systems-thinking or course objectives	Occasional
Pacing, Timing, and Facilitation	References to time constraints, rushed pacing, or facilitation challenges	Frequent
Participation Equity and Group Dynamics	Observations of uneven participation or dominant group members	Occasional
Materials and Scaffolds as Supports	Discussion of examples, visuals, prompts, or support materials	Occasional
Instructor Support and Documentation Needs	Requests for rubrics, guidance, or improved implementation documentation	Frequent

Implications for Curriculum Integration and Sequencing

Student responses related to familiarity and repetition highlight the importance of curricular sequencing when integrating hands-on systems activities across multiple years. Reuse of the same activity can serve different instructional purposes depending on placement within the curriculum, functioning as an introduction in first-year courses and as a shared reference point for deeper analysis in later courses. These findings suggest value in viewing hands-on systems activities as part of a coherent learning trajectory rather than as standalone interventions. Making the role of each activity explicit to students may help maintain engagement while reinforcing systems concepts over time.

Implications for Systems Engineering Education Research

Finally, this work highlights the importance of evaluation-focused research in systems engineering education. Much of the existing literature emphasizes activity development and classroom implementation, while fewer studies examine how activities function across varied instructional contexts or how multiple forms of evidence can inform refinement. By integrating student perceptions, instructor feedback, and emerging assessment artifacts, this study demonstrates a practical approach to instructional evaluation that balances feasibility with rigor.

For the Systems Engineering community, these findings reinforce the value of iterative, evidence-informed approaches to curriculum design and suggest directions for future research that examine longer-term learning outcomes, transfer of systems thinking across courses, and the role of instructional supports in sustaining systems-oriented learning.

Limitations and Future Work

This study has several limitations that shape the interpretation of its findings. Although the activities were implemented across multiple institutions, detailed survey and qualitative data were drawn primarily from a subset of course offerings, limiting the ability to generalize results broadly. In addition, the evaluation emphasizes short-term outcomes such as student perceptions, instructor experiences, and immediate sensemaking around systems concepts rather than long-term learning or transfer.

Assessment of conceptual understanding is still evolving. While post-activity quizzes were developed to probe targeted systems thinking and systems engineering concepts, analysis of these data is ongoing and therefore not fully reported here. As a result, conclusions about learning outcomes remain descriptive and formative.

Future work will focus on completing quiz analysis, examining relationships between hands-on activity participation and engagement with online modules, and refining a fourth activity centered on rapid prototyping and solution-neutral design. Longer-term studies that track how early exposure to systems thinking and systems engineering influences later coursework and design performance will further strengthen understanding of the role of hands-on systems activities in undergraduate engineering education.

Conclusion

This paper presented an evaluation and refinement of three hands-on systems thinking and systems engineering activities implemented in first-year mechanical engineering courses across multiple institutions. By examining student perceptions, open-ended feedback, instructor reflections, and emerging assessment artifacts, the study provides evidence that activity-centered approaches can effectively engage novice learners in systems-oriented thinking when thoughtfully designed and facilitated.

Across activities, students consistently reported high engagement and perceived learning value, particularly when activities emphasized physical interaction, collaboration, and reflection. Instructor feedback highlighted the importance of facilitation, pacing, and scaffolding to support abstraction and system-level reasoning. These findings informed targeted refinements to instructional materials, activity sequencing, and facilitation, demonstrating how formative evaluation can improve instructional design without sacrificing adaptability or scalability.

By shifting the focus from activity development to evidence-informed refinement, this work contributes practical insight for educators seeking to integrate systems thinking and systems engineering concepts into introductory engineering curricula. Embedding these perspectives early supports the development of foundational habits of mind that prepare students to engage with increasingly complex, interdisciplinary engineering challenges throughout their academic and professional careers.

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