International Technology and Engineering Educators' Association 88th Annual Conference Proceedings

A PUBLICATION OF ITEEA AND ITS COUNCIL ON TECHNOLOGY AND ENGINEERING TEACHER EDUCATION RESEARCH AND SCHOLARSHIP COMMITTEE

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The Council on Technology and Engineering Teacher Education (CTETE) supports the mission of ITEEA by providing leadership in the areas of research, standards, and professional development for technology and engineering teacher educators. Members of CTETE have access to valuable teacher education resources including CTETE Yearbooks, the *Journal of Technology Education*, and the contemporary issues in technology education book series. In addition, CTETE members can present research-based findings at the ITEEA Annual Conference. For several years, CTETE, in collaboration with ITEEA, has been pursuing the opportunity for technology and engineering education professionals to publish scholarship in the form of a published proceeding in connection to the annual ITEEA conference. The CTETE Executive committee has felt this is a much-needed scholarship opportunity, not only to general CTETE membership but especially for graduate students and early career professionals. I hope that you will find this inaugural publication, informative, and helpful in your professional responsibilities.

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Technology Education: Supporting the First-Year College Experience

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Abstract

The first-year experience of college is a pivotal time for students adjusting to academic and social demands. At Rhode Island College, the Technology Education program supports the First Year Experience transition through design-based learning rooted in the engineering design process—define, ideate, prototype, test, and evaluate. In the course, FYS 100 - Technological Design and Innovation*, freshman students from all majors engage in open-ended projects that promote creativity, resilience, and reflection while developing critical-thinking, communication, collaboration, and research skills. Writing and documentation are used as tools for inquiry, while oral presentations and teamwork build confidence, belonging, and personal identity. Research is integrated into every stage of design, helping students apply evidence-based reasoning and connect theory with practice. The program's emphasis on active learning, collaboration, and reflection fosters engagement, persistence, and a strong sense of community among diverse learners. Ultimately, Technology Education at Rhode Island College demonstrates how design-centered pedagogy transforms first-year learning—helping students build not only projects but also identity, purpose, and the mindset for a lifelong passion for innovation and learning.*

Keywords: First-Year Seminar, Technology Education, General Education Goals

Introduction

The first year of college represents one of the most critical transitions in a student's educational journey. New students must adapt to increased academic expectations, unfamiliar social environments, uncertain career goals, mental health and well-being, personal responsibilities, and the foreign sense of isolation. Research consistently shows that engagement, belonging, and early academic success are strong predictors of persistence beyond the first year (Stokoe et al., 2024 & van Herpen, et al., 2020). At Rhode Island College, the First-Year Experience (FYE) is intentionally designed to support students during this transition through coordinated institutional efforts, seminar-based coursework, and high-impact teaching practices. Among these efforts, the Technology Education program provides the FYE a compelling model for how design-based, inquiry-driven learning can anchor first-year success.

This essay examines the First-Year Experience at Rhode Island College through the lens of institutional priorities and classroom practice. It focuses particularly on how a Technology Education course framework supports freshmen by fostering critical and creative thinking, communication skills, research fluency, collaboration, and a sense of academic identity. Using Technology Education content and methods as organizers for content delivery and activities, this paper maintains that hands-on, design-centered pedagogy aligns closely with Rhode Island College's broader FYE goals and offers a scalable model for supporting student engagement, persistence, and success during the first year of college.

The First-Year Experience at Rhode Island College

The first year of college represents one of the most critical transitions in a student's educational journey. New students must adapt to increased academic expectations, unfamiliar social environments, uncertain career goals, mental health and well-being, personal responsibilities, and the foreign sense of isolation. Research consistently shows that engagement, belonging, and early academic success are strong predictors of persistence beyond the first year (Stokoe, et al. 2024 & van Herpen, et al 2020). At Rhode Island College, the First-Year Experience (FYE) is intentionally designed to support students during this transition through coordinated institutional efforts,

seminar-based coursework, and high-impact teaching practices. Among these efforts, the Technology Education program provides the FYE a compelling model for how design-based, inquiry-driven learning can anchor first-year success.

This essay examines the First-Year Experience at Rhode Island College through the lens of institutional priorities and classroom practice. It focuses particularly on how a Technology Education course framework supports freshmen by fostering critical and creative thinking, communication skills, research fluency, collaboration, and a sense of academic identity. Using Technology Education content and methods as organizers for content delivery and activities, this paper maintains that hands-on, design-centered pedagogy aligns closely with Rhode Island College's broader FYE goals and offers a scalable model for supporting student engagement, persistence, and success during the first year of college.

Huebeck (2024) noted the trend in college preparedness is declining systemically. Her commentary highlighted the historic lows of inadequate academic readiness. In 2022, the United States witnessed the lowest ACT scores in 30 years and declining SAT scores. Yet, four out of five high school students felt prepared for college. The result is students arriving on campus and having jarring classroom experiences.

Rhode Island College's FYE philosophy reflects a shift away from remediation and toward intentional transition design. Seminar-style courses, active learning strategies, and structured reflection are used to help students make sense of their new environment. Students are encouraged to view themselves as capable learners and emerging professionals, developing confidence as they navigate academic challenges. Agricola, et al., (2024) maintained that support systems in higher education can greatly contribute to the success of first-year students and seamlessly integrate into their new environment. The Technology Education program's contribution to the First-Year Experience is a First-Year seminar course, entitled *Technological Design and Innovation*; that aligns naturally with these institutional goals. As a course, one of over 30 choices per semester, that enrolls students from a wide range of majors, it functions as both an academic gateway and a community-building experience for all participants. The course structure mirrors the broader FYE emphasis on coordination, engagement, and transition support, making it an effective example of how institutional priorities are realized at the classroom level across the campus.

Technology Education as a First-Year Experience Model

The Technology Education program at Rhode Island College supports first-year students through design-based learning rooted in the engineering design process. Students engage in defining problems, generating ideas, prototyping solutions, testing outcomes, and evaluating results. This continuous process provides structure while allowing for creativity and experimentation, making it particularly well suited for students who are new to college-level expectations.

Unlike traditional lecture-based courses, *Technological Design and Innovation* emphasizes learning by doing. Students are immediately immersed in hands-on challenges that require them to think critically, work collaboratively, and communicate their ideas. This approach demystifies college learning by making expectations explicit and processes visible. Students learn that struggle, revision, and failure are not signs of weakness but integral parts of learning. For freshmen navigating uncertainty and self-doubt, this message is powerful. The design process normalizes iteration and resilience, helping students develop confidence in their ability to tackle complex problems. In this way, Technology Education supports not only academic skill development but also the emotional and psychological dimensions of the first-year transition.

Table 1 provides an overview of the assignments/learning activities and goals of the course. The narrative following the table provides an outline and illustrative examples of activities and experiences that occur within the FYS classroom.

Table 1. First Year Seminar (FYS) – General Education Outcomes and Assignments

General Education Outcome	Assignments and Learning Activities
Critical and Creative Thinking	**Students engage in hands-on activities that require them to:** 1. Design, make, and test solutions to simple design problems. 2. Create basic design ideas for product development. 3. Interpret and report information related to technological design and innovation.
Written Communication	**Written communication skills are developed through:** 1. Design sheets and design journals used to record ideas and solutions. 2. Two technology review papers that generate ideas and discussion related to technological innovation and design processes. 3. Design worksheets that allow students to record data, observations, and design ideas.
Research Fluency	**Students develop research skills through the use of the engineering design loop, a widely recognized framework for organizing and refining ideas. This process:** 1. Provides continuity across class activities. 2. Emphasizes communication skills embedded in the design process. 3. Requires students to develop design briefs focused on problem identification, internet and library research, collaboration, and the design, building, and testing of solutions using RIC resources.
Oral Communication	**Oral communication skills are developed through:** 1. Weekly class discussions in which students present ideas from readings and observations of innovations and inventions. 2. Small-group discussions related to projects and readings, with groups reporting out to the class. 3. Formal oral presentations delivered by all students.
Collaborative Work	**Collaboration is a core component of the course and includes:** 1. Group-based problem-solving and design challenges. 2. Teamwork focused on creating and testing solutions to scenarios posed in class. 3. Group presentations in which teams share results and design processes with classmates.

* Table edited by AI for clarity

Critical and Creative Thinking in the First Year

One of the central goals of the First-Year Experience at Rhode Island College is the development of critical and creative thinking. *Technological Design and Innovation* addresses this goal directly by engaging students in open-ended design problems. Rather than following predetermined instructions, students must interpret constraints, identify needs, and make informed decisions. Activities such as designing, making, and testing solutions require students to analyze information, apply concepts, and evaluate outcomes. These tasks mirror the kind of thinking expected with interdisciplinary learning from the sciences and the humanities. By situating critical thinking within tangible projects, the course helps students see its relevance beyond abstract academic exercises.

Creative thinking is equally emphasized. Students are encouraged to generate multiple ideas, explore unconventional solutions, and take intellectual risks. This emphasis aligns with FYS objectives that seek to cultivate curiosity and adaptability. As students learn to navigate ambiguity and complexity, they develop habits of mind that support success throughout their college experience. Most importantly, these experiences also build resilience. Goodrich et al., (2023) citing other resilience research indicated that embedding resilience building

in FYE programs would assist students not only in their first year of study, but later in their academic careers, and possibly into their chosen careers. When designs fail or require revision, students practice persistence and problem solving.

A representative example of this approach is a sustainability focused design challenge centered on the approximately 250 million used tires generated annually in the United States (USTMA, 2023). Framed within the principles of reduce, reuse, and recycle, students work in small groups to develop safe and innovative solutions for repurposing discarded tires. Through collaborative brainstorming and targeted research, groups investigate existing approaches while also examining the controversial science surrounding the chemicals used in tire manufacturing, prompting consideration of environmental and health implications. Teams then build consensus around a proposed solution and communicate their ideas through iterative design practices, beginning with thumbnail sketches, refining concepts into detailed drawings, constructing models, and ultimately presenting their work to the class. This activity exemplifies how students engage in complex problem solving while integrating technical knowledge, ethical considerations, and creative design.

The iterative nature of the engineering design process also aligns closely with growth mindset theory. Growth mindset research suggests that students who view intelligence and ability as developable through effort and learning are more likely to persist when confronted with challenges (Yeager & Dweck, 2012). The design process: define, ideate, prototype, test, and evaluate; naturally reinforces this perspective by framing problem solving as an evolving process rather than a single correct outcome. Students learn that initial ideas are rarely final solutions and that improvement emerges through cycles of experimentation, feedback, and revision. In this context, setbacks become expected features of the learning process rather than indicators of failure. For first-year students navigating the uncertainties of college-level work, the iterative structure of design-based learning provides a concrete model for how effort, reflection, and adaptation lead to improvement over time.

Design-based learning environments also create opportunities for what educational researchers describe as productive failure. When students test prototypes that do not initially perform as expected, they are required to analyze outcomes, reconsider assumptions, and refine their designs. These moments of revision promote metacognitive awareness and encourage students to view challenges as opportunities for growth (Kapur, 2008 & 2016). Within the First-Year Seminar context, such experiences can be particularly valuable because they help normalize struggle during the transition to college. By embedding cycles of feedback and redesign into coursework, the *Technological Design and Innovation* course supports the development of resilience, persistence, and confidence. Explicitly connecting iterative design practices with growth mindset principles strengthens the theoretical grounding of this work, highlighting how design-based pedagogy supports both cognitive development and the adaptive learning dispositions essential for student success in the first year of college. Developing resilience is essential during the first year, when academic and personal challenges often intersect. In this course students are offered opportunities to practice resilience and coping skills championed by Harvey (2007).

Writing and Written Communication

Writing plays a critical role in the First-Year Experience at Rhode Island College, serving as both a mode of communication and a tool for learning. Koch, et al., (2018) advocated that integrating literacy opportunities in STEM coursework, "…improves literacy skills in the context of a hands-on, problems-based, team-oriented curriculum." During *Technological Design and Innovation*, writing extends beyond traditional essays to include design journals, worksheets, research summaries, technology interest narratives, and reflective documentation. This multimodal approach helps students connect thinking processes with outcomes and mirrors what might be found in real-world situations.

Design journals and design sheets require students to articulate ideas, record observations, and reflect on decisions. These practices support metacognition by encouraging students to examine how they think during our

design activities. Technology review papers introduce students to academic research and formal writing conventions, helping them develop confidence in navigating college-level literacy requirements. This integration of writing aligns with FYE goals that emphasize writing across contexts. Students learn that writing is not confined to English courses but is a fundamental skill across disciplines. By embedding writing into hands-on projects, it becomes purposeful and relevant, reducing anxiety and increasing engagement. This approach supports the first-year students' transition from high school writing to college-level communication. Students practice clarity, organization, and evidence-based reasoning in authentic contexts, laying a foundation for future academic work. Writing activities provide students with chances to explore the many academic support services on the campus. We value the good work of the Writing Center and our library for providing their assistance to FYS students who want to improve their writing skills and to develop their ideas.

Research Fluency and Inquiry-Based Learning

Research fluency is another foundation of the FYS at Rhode Island College. Students are expected to engage with credible sources, navigate library and web resources, and apply evidence to support their ideas. Students' selected projects integrate research into every stage of the design process, making inquiry an active and ongoing practice. Students begin with design briefs that frame problems and identify constraints. They then conduct research using resources such as the internet, databases, local experts, and Rhode Island College's library materials. This research informs design decisions and helps students connect theory with practice. By embedding research within projects, *Technological Design and Innovation* activities demystify academic inquiry and build confidence in students' ability to engage with complex information. This approach aligns with institutional FYS goals that emphasize structured inquiry and information literacy. Rather than treating research as a one-time assignment, weekly lessons present it as a tool for problem solving and innovation. Students learn to ask questions, evaluate sources, and apply findings in meaningful ways. For freshmen, developing research fluency early is critical. It supports academic success across courses and fosters a sense of competence and independence. The course's emphasis on applied research provides a supportive entry point into college-level inquiry.

Oral Communication and Student Voice

Oral communication is an essential component of the FYS, supporting both academic success and personal development. During our weekly class activities, we integrate speaking and presentations throughout the course, from informal discussions to formal presentations of design solutions and the impact of technology on their own lives. Weekly student-led discussions and small-group reporting sessions provide low-risk opportunities for students to share ideas and practice articulation. Formal presentations require students to organize thoughts, explain processes, and respond to questions raised by their peers. These experiences help students develop confidence and clarity in expressing their ideas. The focus on oral communication aligns with FYS objectives that emphasize student voice and academic identity. As students learn to speak in academic settings, they begin to see themselves as contributors to knowledge. This sense of belonging and legitimacy is particularly important during the first year, when many students question whether they belong in college. By embedding oral communication within collaborative, hands-on work, these activities reduce performance anxiety and promote supportive peer interactions. Students learn that communication is a shared responsibility and a key component of successful teamwork.

Collaboration, Belonging, and Community

Collaboration is a defining feature of both the First-Year Experience at Rhode Island College and in the *Technological Design and Innovation* classroom. Students work in design teams to solve problems, share responsibilities, and present solutions. These collaborative experiences reflect real-world practices and reinforce the value of teamwork. Group work supports FYS goals related to community and belonging. Forming connections with peers is critical to first-year students' growth in persistence and well-being. This FYS experience creates

structured opportunities for interaction, helping students build relationships around shared goals. Through collaboration, students also develop interpersonal skills such as communication, conflict resolution, and accountability (Worsley, 2021). Mattson (2025) proposed, "Evidence suggests holistic student development secures greater success than academic skill enhancement alone, so it is important that the college ideal and character development should equally coexist (p. 33). These skills support academic success and prepare students for professional environments. Importantly, collaborative work helps students see diversity of perspectives as a strength, fostering inclusive learning communities. By emphasizing teamwork from the outset, the many activities that students engage in reinforce the idea that learning is a social process. This message aligns with Rhode Island College's commitment to creating a coherent and supportive first-year experience for all students.

Conclusion

The First-Year Experience at Rhode Island College is shaped by intentional design, institutional commitment, and coordinated support across the campus. Through initiatives such as FYS and a focus on coherent student experiences, Rhode Island College positions the first year not as a barrier to overcome, but as a guided entry into academic culture. Institutional buy-in and alignment ensure that students encounter consistent expectations, supportive learning environments, and opportunities to build confidence and belonging.

Technological Design and Innovation exemplifies how these institutional priorities can be enacted through classroom practice. By integrating hands-on design challenges, structured inquiry, and collaborative learning, the program supports freshmen academically, socially, and emotionally. Students develop critical and creative thinking, writing and research fluency, oral communication skills, and the ability to work effectively with others—competencies that align directly with Rhode Island College's First-Year Experience goals.

Moreover, activities derived from Technology Education curriculum contribute to a coherent first-year experience by reinforcing skills and dispositions introduced in FYS seminars while offering a distinctive, applied context for learning. The engineering design process provides structure during a time of transition, helping students navigate uncertainty, build resilience, and develop a sense of purpose.

As Rhode Island College continues to strengthen and refine its First-Year Seminar initiatives, *Technological Design and Innovation* offers a scalable and transferable model. It demonstrates that when institutional vision, curricular design, and pedagogy are aligned, first-year courses can do more than support student retention—they can help students form academic identity, community connection, and a lifelong mindset for learning, innovation, and engagement.

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Measuring the Impact of Self-Evaluation Practices

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Abstract

Structured self-reflection is widely recognized as a valuable component of student learning, yet research quantifying its impact in post-secondary settings remains limited. This study examines the use of a formal self-evaluation tool designed to foster metacognitive awareness, ownership of learning, and skill development across diverse educational contexts. The tool was implemented in project-based Career and Technical Education (CTE) courses and presentation-based teacher education courses, with participants assigned to either a treatment group that completed the tool or a control group that engaged in standard course activities. Across five courses and six semesters, self-reported growth was measured through pre- and post-course surveys. Results indicate that while overall growth differences between treatment and control groups were modest (2.75% on average), the tool may have promoted more nuanced reflection on specific skills and increased awareness of areas for improvement. Variability across courses highlights the influence of prior experience, assessment frequency, and course type on self-evaluation outcomes. Findings suggest that structured self-assessment can support reflective learning and inform instructional practices, though its impact may be maximized when integrated consistently throughout a course. The study provides practical insights for educators seeking to implement formal reflection tools and highlights directions for future research to enhance student self-assessment.

Keywords: Self-evaluation, Reflection, Scholarship of Teaching and Learning

Introduction

Giving and receiving feedback on original works has been the cornerstone of education for a century. Traditionally, students complete and turn in a project, paper, or presentation, and instructors grade the work via a rubric, providing specific feedback that highlights strengths and areas for improvement. While instructor feedback is critical, feedback from peers or the students themselves also plays a powerful role in learning.

It is widely accepted that self-evaluation practices are invaluable for student understanding and ownership of learning. John Dewey discussed reflective practices over a century ago, and many educators continue to incorporate informal self-assessment in their teaching. However, informal approaches can be inconsistent, subject to bias, or lack structured guidance, and few studies have quantified the impact of formalized self-evaluation on student growth in self-reflection skills and subject-matter competencies across multiple post-secondary disciplines.

To address this gap, the researchers developed a formal self-evaluation tool for use in a variety of post-secondary educational settings. This study tests the tool across multiple courses and disciplines to examine its impact on student-reported growth, confidence, and skill development. By providing a structured, repeatable method for reflection, the tool aims not only to support student learning but also to inform instructors' teaching practices.

Literature Review

Reflective practices are not new in teaching. John Dewey published on reflective practices in education from 1910 through the 1930s and beyond. More recently, Farahani (2025) reinforces Dewey's thoughts by stating, "One of the most effective - and often overlooked - ways to cultivate these [self-evaluation] capabilities is through reflection and self-assessment." The overall focus of the reflection process for this paper is on the learner's motivation and ownership and on professors' responsibilities, using student self-evaluations to im-

prove student learning. Reflective practices take time to develop; however, they can make teaching more efficient and encourage revision of course material to improve teaching and student learning (UCLA Teaching and Learning Center (TLC), 2025).

It should be noted that self-ratings are not a perfect tool for reflection. Some students rate themselves higher or lower than expected. Some students have perfectionistic tendencies and rate themselves more harshly than others on rating scales (Hill, 2017). While some students rate themselves too harshly relative to the professor's grades and ratings, others rate themselves much higher than the professor would. This may be due to rubrics or surveys that lack appropriate descriptors or overly vague scales (Gavin et al., 2015). However, self-assessment is important for students, helping them take an active role in responsibility for their own learning (Yan & Carless, 2022). In the reflection process, it is important to consider its timing, depth, and content (Machost & Stains, 2023).

Accurate self-assessment can be achieved when a constructive attitude focuses on improvement, and we should take the opportunities to do better when available (Weimer, 2024). Educators should set the tone that every piece of work can be improved. Professors can encourage constructive feedback and reflection by asking students, "When you do this next time, how will you improve it?" when these opportunities arise in the classroom. This paper addresses students' reflective practices in their coursework and professors' reflective practices as they review students' reflection tools.

Methodology

Approach

This study employed a partial single-blind design to examine the effectiveness of a formal self-evaluation tool on student self-reported growth. Participants were randomly assigned within each course section to either a treatment or a control group using a random number generator. The treatment group in each class completed the self-evaluation tool following a major project or presentation, and the control group completed the same course activities but did not complete the structured self-evaluation tool. Self-reported growth was compared between groups to assess the intervention's potential impact.

To maintain blinding, the researcher who did not teach the course had no knowledge of which students had consented to participate or to which group participants had been assigned. Data were not reviewed until all course grades had been finalized at the conclusion of each semester.

Participants

Participants were undergraduate students enrolled in postsecondary courses taught by the researchers. Participation was voluntary, and all students were informed of data collection procedures and their rights as participants. Students who agreed to participate provided informed consent. Data from students who did not provide consent were excluded from analysis, although these students continued to participate fully in all assigned course activities without penalty.

Methodological Tools

Data were collected using a series of electronic self-evaluation instruments administered via Google Forms. These instruments included an Opening Self-Evaluation Survey (OSES), a formal self-evaluation tool administered to the treatment group, and a Closing Self-Evaluation Survey (CSES).

The OSES and CSES shared identical formats and question sets and consisted of two sections: demographic information (e.g., age, academic classification) and a self-evaluation of perceived understanding and skill related to course objectives. Participants rated themselves using a numeric scale, with higher values indicating greater confidence, skill, or understanding. Students were instructed to complete all self-evaluations as accurately and honestly as possible.

The formal self-evaluation tool was structured similarly to the OSES and CSES, but it prompted students to evaluate the quality and completeness of their completed work across multiple criteria using a numeric rating scale.

Implementation

Following presentation of the research and consent information, the instructor of record exited the classroom while the second researcher collected consent forms and administered the OSES. Similar procedures were used during subsequent survey administrations to ensure participant anonymity. Specific implementation procedures varied by course section and semester and are described later in this section.

Immediately after the consent process, participants completed the OSES via a QR code or a link embedded within the course learning management system (LMS). After completing the opening survey, courses proceeded as normal, with no modifications to instructional content or pedagogy.

The formal self-evaluation tool was delivered electronically via the LMS following completion of a major project or presentation. At the conclusion of the semester, all consenting participants completed the CSES using a QR code or LMS link. Self-reported growth was calculated by comparing opening and closing self-evaluation scores, and the potential effectiveness of the formal self-evaluation tool was assessed by comparing observed growth between the treatment and control groups. To date, only three students have been in multiple courses in which the surveys have been administered.

Fall 2024: TECS180 – Materials, Processes, and Production (Figure 1).

Initial data were collected in Fall 2024 from two sections of TECS180, a project-based course focused on safe and productive operation of wood, metal, and plastics manufacturing equipment. The primary assignment was the construction of a small grain truck toy, intentionally designed to require the use of major machines across all laboratory areas. Although plastic wheels could not be mass-produced due to equipment malfunctions, plastic processes were still demonstrated and wooden wheels were substituted.

Research briefings and informed consent were completed during the first week of the semester. Students completed the project by late October. Assignment to treatment or control conditions occurred at the section level. On the evaluation day, both sections brought completed projects to a location separate from the course instructor. Researcher Two administered the formal self-evaluation tool to the treatment group, while control group participants completed an unrelated activity to mask group assignment. The CSES was administered during finals week, concluding data collection for this course (Figure 1).

Spring 2025: TEACH302 – Educating Exceptional Students (Figure 2).

In Spring 2025, data were collected from sections of TEACH302, a lecture-based course emphasizing instructional strategies for teaching students with diverse learning needs. Differentiation skills were practiced through peer-taught lesson presentations. Researcher One conducted the research briefing, consent process, and survey administration.

The same Google Forms instruments used in TECS180 were used, with survey items modified to align with course-specific learning outcomes and the 4-point Likert scale adjusted to a 10-point scale to improve response sensitivity and self-assessment precision. Students rated confidence in lesson preparation, peer instruction, and responsiveness to feedback. Expanding the scale provided students with more gradations for reporting perceived growth, helping capture smaller differences in self-evaluated performance that might otherwise be compressed within a narrower response range.

The OSES was administered immediately following consent. During finals week, treatment group participants completed the formal self-evaluation tool followed by the CSES, while control group participants completed only the CSES. Survey links were distributed via email following each student's final presentation.

Spring 2025: TECS280 – Woods Processes (Figure 3).
Additional data were collected using the modified instrument in Spring 2025 from TECS 280, a project-based woodworking course focused on furniture design and construction. Survey instruments were adapted from TECS180 to include criteria specific to furniture fabrication, and the formal self-evaluation tool was aligned with the construction quality of student-built nightstands.

Procedures mirrored those used in TEACH302. Researcher Two administered the research briefing, consent materials, and OSES early in the semester. The formal self-evaluation tool and CSES were administered to treatment and control groups during finals week.

Fall 2025: Methodological Refinements (Figures 4 and 5).
Prior to Fall 2025, data collection procedures were refined to streamline survey distribution while maintaining anonymity and experimental control. For Fall 2025 sections of TECS 180 and TEACH302, the timing of data collection remained unchanged, but individual QR codes replaced email-distributed survey links.

Treatment group participants received QR codes that linked to the formal self-evaluation tool, while control group participants received QR codes that linked to a neutral, time-matched survey containing non-evaluative items. This approach preserved blinding and minimized participants' awareness of group assignment. Data from Fall 2025 TECS 180 are reported in Figure 4, and data from Fall 2025 TEACH302 are reported in Figure 5.

Results

The following charts summarize the data collected from each of the five courses used in the study. Each bar graph shows the average percentage of self-reported growth from students in five separate classes.

The X-axis of the charts shows the seven categories for which students rated their confidence and skills at the beginning and end of each class. "Reported Growth Percentage" on the Y-axis shows the percentage of growth calculated by subtracting the average opening score from the average closing score, then dividing by the average closing score.

In addition to the results below, we compared the survey results using chi-square tests, which indicated that all participating students showed statistically significant growth in our classes. However, the control group showed marginally more growth. Both groups changed significantly over the semester, but the group that used the formal self-evaluation tool experienced larger shifts in their responses. This suggests the tool may have enhanced student awareness of their growth, resulting in greater movement between the response categories.

Figure 1.
F24 - TECS180 (N-19)

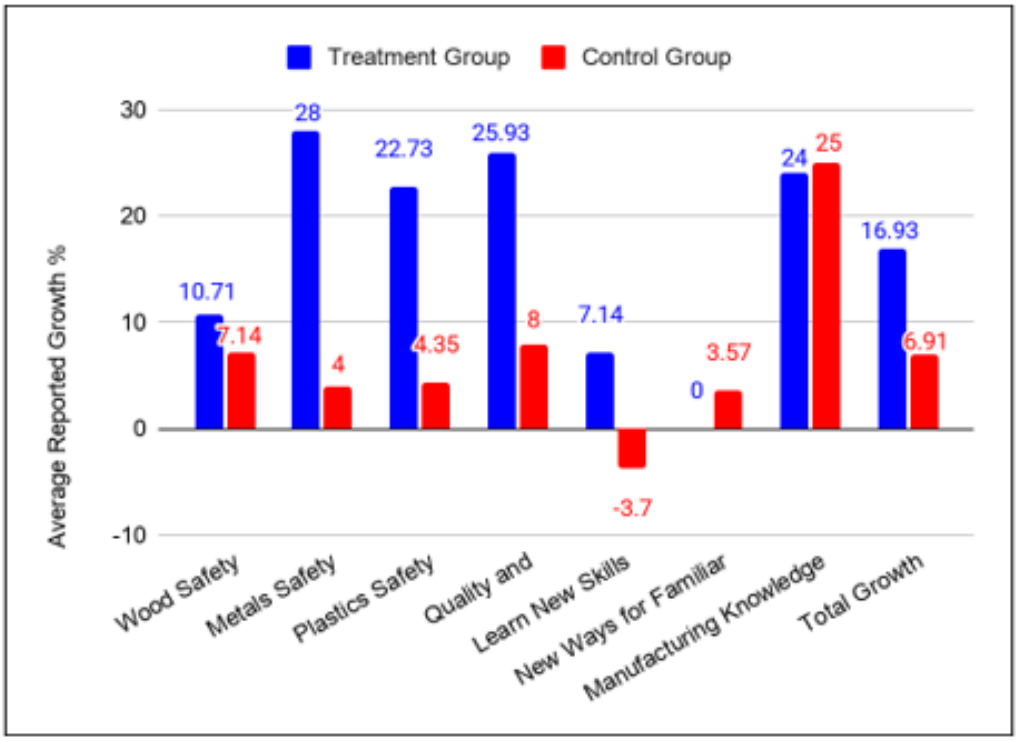


Figure 2.
S25 - TEACH302 (N-26)

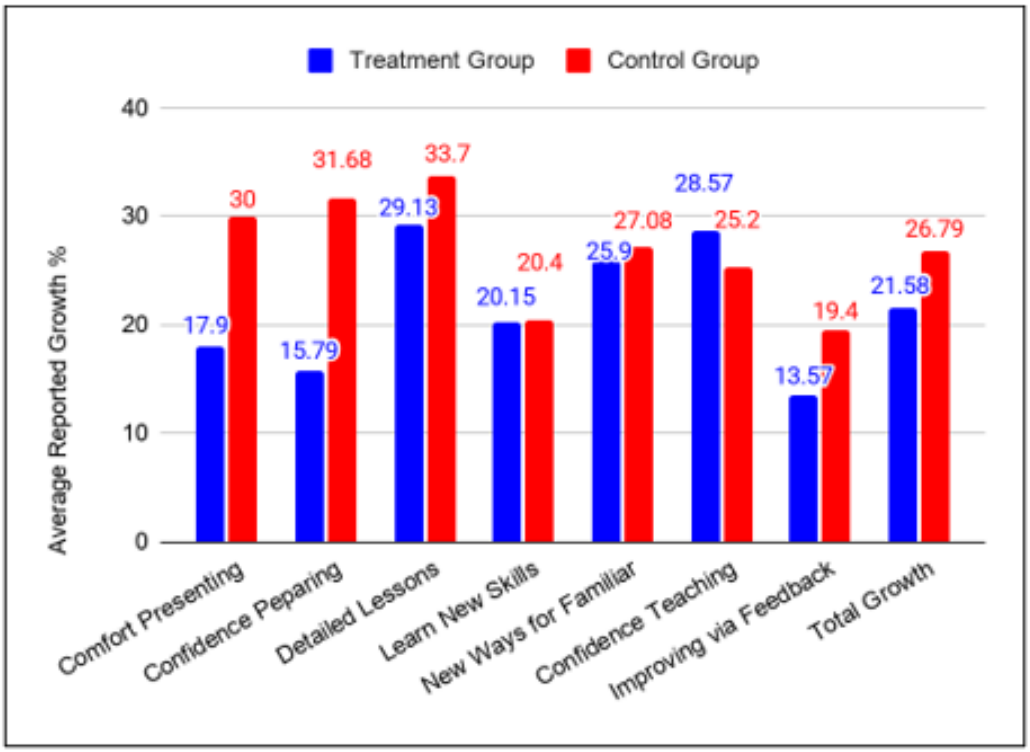


Figure 3.
S25 - TECS280 (N-8)

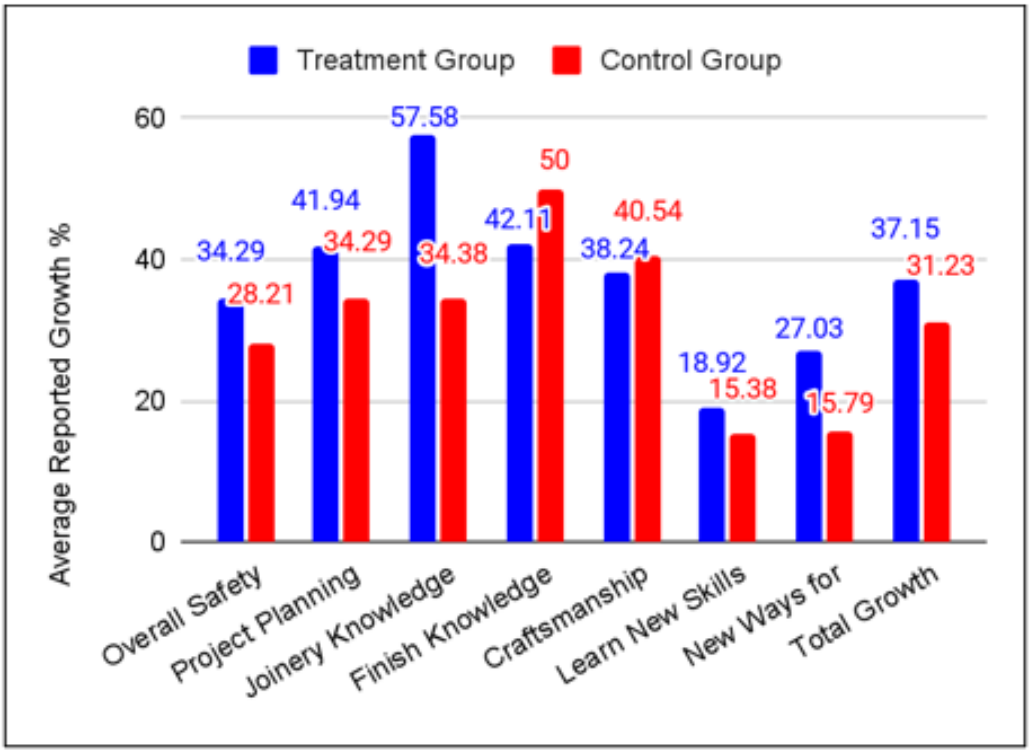


Figure 4.
F25 - TECS180 (N-46)

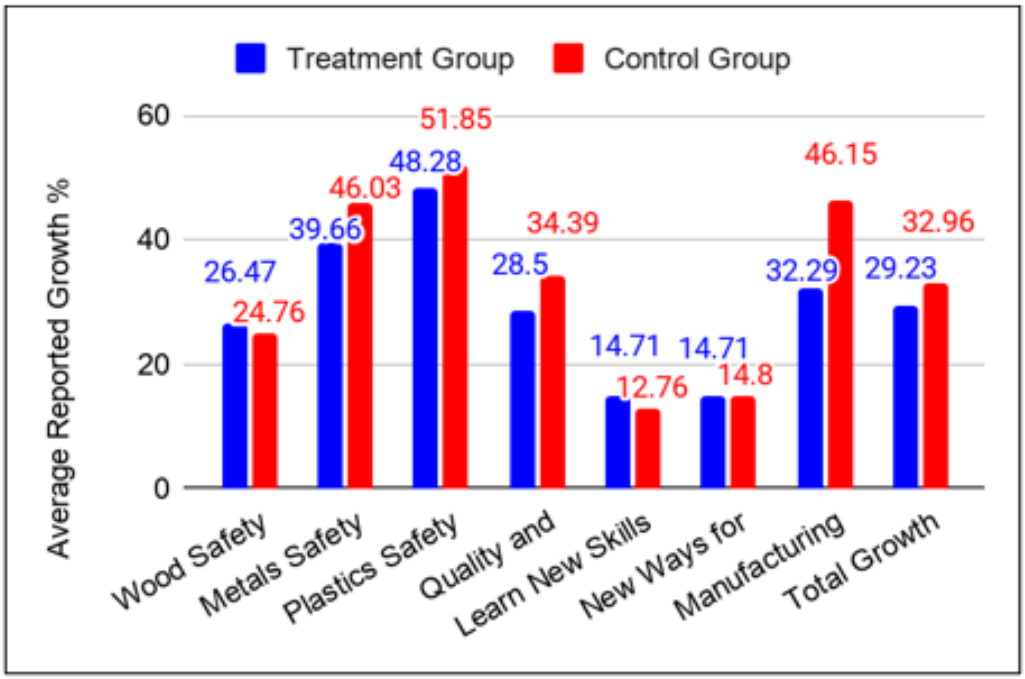
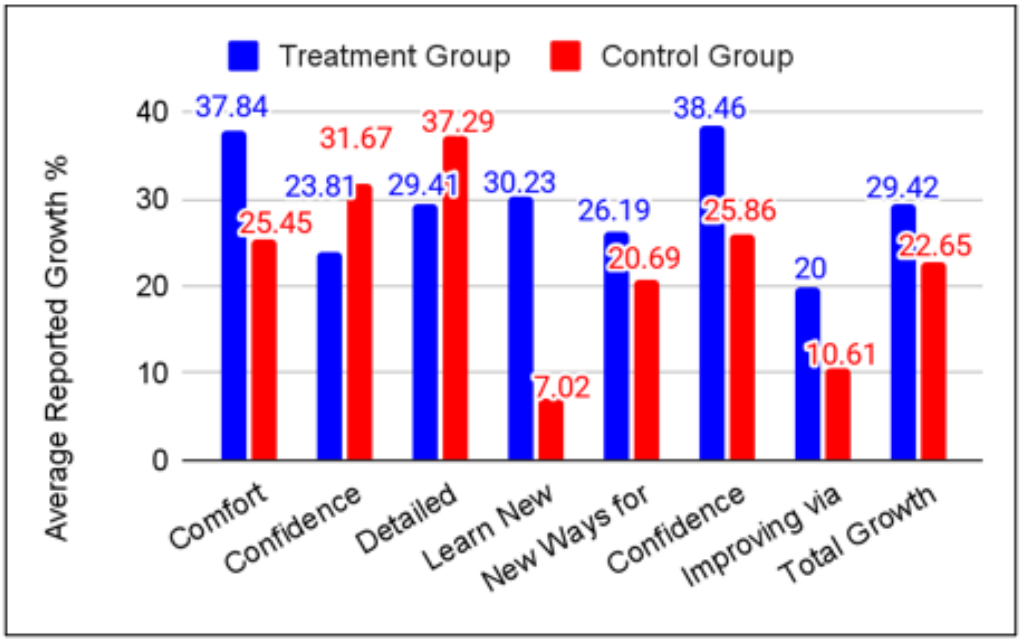


Figure 5.
F25 - TEACH302 (N-12)



Discussion

It is important to note that every group showed growth and increased understanding, regardless of the group to which they were randomly assigned. Not all data sets appear to demonstrate a positive impact of the Self-Evaluation Tool. When averaging total growth across the five courses, the Tool group reported only a 2.75% higher growth than the control group. These results do not indicate that formal self-evaluation practices are ineffective, but they do suggest the need for continued refinement in the Tool's implementation within daily class activities.

The first set of data showed the Tool's greatest positive impact, with the treatment group reporting roughly 10% more growth than the control group, prompting the researchers to replicate the process with minor adjustments in subsequent semesters. Minor adjustments to the survey will continue as necessary to meet student and instructor needs.

In Figure 2, the treatment group showed 5% less growth than the control group. This unexpected result was potentially influenced by changes in the data collection process: distributing the survey links via email maintained participant anonymity from Researcher Two but complicated response collection, as CSESs were technically assigned after students completed all coursework. Figures 3 and 5 showed a positive impact for the Tool, with 6% and 10% more total growth, respectively, compared to the control group.

Figure 4, which represented the largest sample in the study, produced another unexpected outcome: the control group recorded higher overall self-reported growth than the treatment group. Category-level analysis suggests this difference was driven primarily by responses in Category 4: Quality and Craftsmanship. In Technology and Engineering Education courses, students often evaluate craftsmanship through direct visual and tactile inspection, which may make this category particularly sensitive to differences in self-assessment. Within the treatment group, 16% of participants assigned themselves the maximum craftsmanship score, compared with 47% in the control group. Given that a maximum score indicated "no mistakes in the production of the project," this pattern may reflect differing interpretations of craftsmanship.

One possible explanation is the Tool itself: students completing the structured self-evaluation were prompted to systematically assess specific project components, likely increasing awareness of minor flaws. As a result, these students rated their craftsmanship more conservatively, even when overall quality was high. In contrast, students without the Tool may have engaged in less structured reflection, leading to more generous self-assessments. This difference in evaluative approach may explain the higher reported growth observed in the control group for this data set.

From the outset, the study intentionally focused on growth rather than learning. Students enter post-secondary courses with widely varying levels of prior experience. For example, in TECS180, some students had multiple years of high school or trade school woodworking experience. While these students may have learned fewer new methods than peers with no prior lab experience, they still demonstrated growth by refining existing skills, adopting more efficient processes, or applying familiar techniques with greater precision. Similar variation was evident in TEACH302, where some students had extensive presentation experience while others had limited exposure. A growth-based, self-evaluation framework allows students to assess change relative to their own starting points, rather than against a uniform standard of “learning.”

Frequency of implementation also matters. When deployed only once during an 80-day semester (roughly 1.25% of instructional time), the Tool’s effect may be limited. The modest 2.75% higher growth in the treatment group may reflect this restricted exposure. Increased frequency could strengthen reflective habits, deepen familiarity with evaluation criteria, and enhance measurable gains.

Beyond these student outcomes, the research process has yielded significant benefits for instructors. The systematic collection and review of self-evaluation data prompted extended reflection on teaching methods, course design, and student needs over six semesters. These discussions improved teaching in both the courses studied and other classes, fostering ongoing pedagogical refinement that is uncommon in higher education.

In Researcher One’s TECS180 class, shop safety is a primary focus. It is essential that students learn to operate each piece of equipment safely and efficiently. Prior to this study, the instructor assessed students’ competence by observing them use the machinery in a controlled setting and ensuring that safety procedures were followed. One question on both the opening and closing surveys asked, “I feel safe when I operate woodworking equipment.” Reviewing the anonymized opening scores allowed the instructor to identify students with little or no experience or who felt apprehensive, enabling adjustments to teaching methods to meet their needs. Similarly, analyzing the closing survey data reveals how comfortable students became with the equipment, providing insights that inform improvements to presentations and instruction in future semesters. Researchers believe that gathering information through the tool’s administration is useful for instructor improvement.

Future research will expand on these findings by incorporating formal peer evaluations in the same courses and conducting interviews with consenting students to better understand their experiences with the self-evaluation process. Aligning teacher evaluations with student self-assessment data is also planned to enhance the interpretation of growth and provide a more comprehensive picture of student development.

Overall, the data indicate potential for the self-evaluation tool. Three of the five treatment groups demonstrated notable growth relative to the control groups, while the two groups that did not show growth may have been affected by inconsistencies in data collection. Beyond the quantitative findings, the research prompted deeper reflection on teaching practices than the researchers had previously undertaken. Student feedback will continue to inform instructional strategies, enabling instructors to refine pedagogy and design curricula that support meaningful growth for all learners.

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Betsy's training, research, and experience help identify students' individual needs and talents by building relationships with them. Strong relationships are key. Learners and educators persevere and are more engaged when working with those who see them as individuals with unique characteristics, abilities, and experiences. Throughout Betsy's classes, she incorporates as many opportunities as possible to develop personal connections with students while maintaining high expectations for all.

Integrating the 5E Instructional Model and the Engineering Design Process: A Practical Approach for Technology and Engineering Classrooms

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Abstract

Teachers often implement engaging design challenges, yet students may focus on construction without developing a strong conceptual foundation. Integrating scientific inquiry with engineering design practices offers a practical solution to this challenge. This paper illustrates how the 5E Instructional Model and the Engineering Design Process (EDP) can be integrated to support meaningful learning using an aluminum foil boat challenge. In practice, students first engage in inquiry around buoyancy and related physical science concepts. Only after the investigation do learners apply that knowledge to design, test, and refine a boat that floats and holds weight. The instructional sequence aligns inquiry-based science learning (Engage, Explore, Explain, Elaborate, Evaluate) with iterative engineering practices (Ask, Imagine, Plan, Create, Improve), allowing students to investigate scientific phenomena while engaging in authentic problem solving. Classroom observations, student artifacts, and reflective discussions were used to examine learning outcomes and instructional effectiveness. This approach can be adapted across a variety of technology and engineering activities, offering a replicable, standards-aligned strategy for practitioners.

Keywords: technology and engineering education, engineering design process, integrated STEM education, design-based learning, inquiry-based instruction

Introduction

Technology and engineering classrooms frequently rely on hands-on design challenges to engage learners in problem solving. The aluminum foil boat challenge is a familiar activity in many classrooms, but its instructional potential is often unrealized when it is treated as a stand-alone task. When paired with a structured learning pathway, the challenge becomes an opportunity to link physical science understanding to meaningful design work.

The 5E Instructional Model is an effective framework for guiding inquiry-based science learning, while the Engineering Design Process (EDP) provides a structured approach for solving technological problems. Each model offers significant instructional value. The 5E model supports investigation, sense-making, and conceptual understanding, and the EDP emphasizes iterative problem-solving under constraints. When integrated intentionally, they provide a powerful connection that bridges scientific understanding and engineering application. These frameworks reflect authentic STEM and workforce practices, where professionals investigate phenomena, analyze data, and apply evidence to improve solutions.

In this integration, the aluminum foil boat challenge will serve as a concrete classroom example to demonstrate how 5E and EDP can be integrated into technology and engineering education through a hands-on design challenge. The 5E model provides a framework for students to engage with, explore, and explain buoyancy-related phenomena before designing and testing in the EDP.

Inquiry-Based Learning and the 5E Instructional Model

Inquiry-based learning has long been recognized as an effective approach for supporting conceptual understanding in science education. Research indicates that inquiry-based instruction improves conceptual understanding, retention, and student motivation by positioning learners as active participants rather than passive recipients of knowledge. The 5E Instructional Model (Engage, Explore, Explain, Elaborate, Evaluate) supports

curiosity-driven exploration and provides a clear structure for concept development. The Engage and Explore phases allow students to investigate phenomena, while Explain and Elaborate support vocabulary development and conceptual refinement. Evaluation emphasizes reflection and formative assessment, aligning well with engineering learning goals. The 5E model is grounded in constructivist learning theory, emphasizing that students build understanding through active engagement with phenomena (Bybee, 2019).

Engineering Design Process in Technology and Engineering Education

While inquiry supports scientific understanding, engineering education emphasizes problem solving through design and iteration. The Engineering Design Process provides students with a systematic approach to solving problems through defining constraints, generating ideas, testing solutions, and iterating designs. Research states that early exposure to engineering practices fosters problem-solving skills, creativity, and perseverance (Stanford et al., 2018). Iteration and failure are critical components of the EDP, helping students develop resilience and an understanding that improvement is an expected part of engineering work.

Integrating Scientific Inquiry and Engineering Design

Although the 5E model and the Engineering Design Process are often implemented independently, research suggests that integrating these frameworks provides a coherent instructional pathway that mirrors authentic STEM practice. Inquiry allows students to understand scientific concepts, while engineering design provides a context for applying that knowledge. This integration supports interdisciplinary learning and aligns with *Standards for Technological and Engineering Literacy (STEL)* by investigating phenomena, building conceptual understanding, and applying that understanding to design and improve functional models.

In practice, the instructional sequence begins with the Engage and Explore phases of the 5E model. Students investigate scientific phenomena through hands-on exploration and inquiry. This investigative phase allows learners to develop conceptual understanding before formal instruction is introduced. In the context of boats and floating, students might begin by observing a variety of objects in water, predicting what will float or sink, and discussing their reasoning. During the Explore phase, students manipulate materials, especially aluminum foil, to see firsthand how shape and surface area affect whether an object floats. At this stage, students test different foil configurations without the pressure of solving a design challenge, which allows them to notice patterns and build raw observational data.

Only after the investigation do formal explanations occur. In the Explain phase, educators introduce vocabulary and scientific concepts, such as buoyancy, density, and displacement, and connect these terms directly to students' observations and questions. Once students have constructed meaning through exploration and explanation, the Engineering Design Process enables them to apply this newly acquired knowledge to construct, test, and refine a model with evidence to guide their decisions. In this way, scientific inquiry becomes the foundation for engineering design rather than a separate, disconnected activity.

The EDP begins with problem definition and continues through brainstorming, planning, and the construction of a functional model. Because students have meaningfully investigated the behavior of materials in water, they can justify design decisions based on data collection during exploration. For example, a group may choose a wider, flatter base because exploration showed that a larger surface area provides greater buoyancy. As students build and test their boats, they are collecting performance data, such as the number of weights a design can hold before sinking. This then informs redesign and refinement. The cycle of test, analyze, and improve mirrors authentic engineering and supports evidence-based reasoning, a core aspect of *STEL*.

Importantly, this integrated approach is not limited to a single activity or content area. The 5E instructional model provides a flexible structure for scientific investigation across a wide range of STEM contexts.

Instructional Design and Learning Sequence

The linked **lesson plan** demonstrates the classroom implementation of an aluminum foil boat design challenge in an elementary STEM setting. The lesson sequence was aligned with physical science and engineering standards and designed to support inquiry, collaboration, and iterative design. The learning sequence integrated the 5E model with the Engineering Design Process across multiple class sessions.

Assessment and Evidence of Student Learning

Evidence of student learning was gathered through a combination of formative and summative assessments embedded naturally in the design challenge. Throughout the activity, students maintained engineering design notebooks, which served as a central tool for documenting observations, sketching ideas, recording test results, and reflecting on design decisions. During the initial inquiry phases, students used their notebooks to note which foil shapes floated or sank, describe changes made during exploration, and capture emerging questions about buoyancy and stability. These early entries provided insight into students' developing scientific understanding prior to formal instruction.

As students progressed into the Engineering Design Process, notebooks became a record of engineering thinking. Students documented design plans, labeled sketches, recorded testing outcomes, and noted reasons for design revisions. This written evidence revealed how students applied scientific concepts introduced during the Explain phase to justify design choices, such as increasing surface area or redistributing weight. The notebook entries demonstrated growth in evidence-based reasoning, as students refined their designs based on test data rather than solely through trial and error.

Formative assessment occurred continuously through teacher observation, questioning, and student use of engineering design notebooks. Observational data included how students collaborated with peers, responded to design constraints, and iterated after unsuccessful tests. These observations allowed teachers to identify misconceptions, provide targeted feedback, and prompt deeper thinking through questioning rather than direct instruction. The informal nature of these assessments supported a student-centered learning environment while maintaining academic rigor.

Summative assessment was supported by a reflective constructed-response writing prompt completed at the conclusion of the challenge. Students were asked to explain how their final design improved over time and to describe which scientific ideas helped their boat hold more weight. Responses demonstrated students' ability to synthesize investigation and design experiences, articulate cause-and-effect relationships, and use appropriate vocabulary. Together, the engineering design notebooks, observational evidence, and reflective writing provided a comprehensive picture of student learning that captured both process and product, a goal of technology and engineering education.

Conclusion

In conclusion, integrating the 5E model and EDP supports meaningful learning by aligning scientific inquiry with engineering application. The structured yet flexible framework allows students to explore phenomena, apply concepts, and iteratively refine solutions. While this paper highlights an aluminum foil boat challenge, the instructional framework can be applied to a wide range of technology and engineering education activities. Whether students are exploring bridges, towers, aerodynamic vehicles, or filtration systems, beginning with inquiry into relevant scientific phenomena ensures that subsequent design work is grounded in evidence. The 5E model first allows students to engage in scientific investigation. Then, students transfer and apply this scientific understanding during the engineering design phase by constructing and refining models that represent their learning. Teachers function as facilitators, guiding inquiry while allowing students ownership over design decisions. This instructional stance supports equity by providing multiple entry points for diverse learners.

Integrating the 5E Instructional Model with the Engineering Design Process offers a practical, standards-aligned framework for technology and engineering instruction. By connecting inquiry-based science learning with iterative design, educators can support deeper conceptual understanding, enhance problem-solving skills, and foster engineering habits of mind. This approach is transferable to many classroom contexts, offering a replicable strategy for practitioners seeking to bridge inquiry and design in meaningful ways.

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Beyond the classroom, she contributes to the broader education community through presentations and writing, including her work with ITEEA, where she shares practical strategies for integrating engineering and inquiry into everyday teaching and learning. Passionate about equity in STEM, Miette strives to inspire the next generation of problem-solvers while supporting fellow educators with effective, research-based practices.

Enhancing Civil Engineering Technology Education with Practical Case Studies on Rainwater Harvesting Systems

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Abstract

Integrating case-based learning (CBL) on rainwater harvesting (RWH) systems into Civil Engineering Technology (CET) education offers an applied approach for connecting theory and practice. The study examines how applied, interdisciplinary learning using RWH case studies supports student engagement and understanding of sustainable water management concepts. An exploratory classroom-based approach combined international case studies with course implementation. Real-world RWH examples from the southeastern United States and India were integrated into CET coursework to evaluate how CBL supports student understanding of sustainable infrastructure. Post-lesson surveys and reflective assessments captured student perceptions and self-reported learning outcomes. Findings indicated positive student perceptions, including reported improvements in understanding of RWH systems, support for the use of CBL, and preferences for CBL relative to traditional lectures. These results suggest that RWH-focused case studies may serve as a useful instructional approach for engaging engineering technology students with sustainability-oriented, applied engineering problems related to water and climate challenges.

Keywords: Rainwater Harvesting (RWH), Civil Engineering Technology (CET), Case-Based Learning (CBL), Engineering Education, Case Studies

Introduction

Climate change, rapid urbanization, and population growth are placing increasing strain on global water resources, highlighting the need for resilient and sustainable management strategies. Low Impact Development (LID) applies sustainable design strategies in stormwater management by mimicking natural hydrology through practices like RWH systems, rain gardens, permeable pavements, and green roofs to reduce runoff, improve water quality, and enhance groundwater recharge (Chathuranika et al., 2026). RWH offers a low-cost, environmentally sound solution to supplement conventional water supplies. By capturing and storing rainwater for non-potable uses such as irrigation and sanitation, RWH reduces reliance on municipal and groundwater sources while supporting stormwater control and flood mitigation. Consequently, RWH contributes to long-term water security, environmental stewardship, and global sustainability goals, particularly Sustainable Development Goal 6.

Addressing these challenges requires engineering education to move beyond theory-focused instruction (Ismael, 2023). Preparing future civil engineers demands applied, interdisciplinary learning that reflects real-world complexity. CET programs, with their emphasis on hands-on and skill-based training, are well suited to embed sustainability into curricula. However, many programs remain rooted in traditional pedagogies with limited experiential problem-solving opportunities (Ribeiro and Mizukami, 2005), leaving graduates underprepared to apply theoretical knowledge to environmental and societal challenges. However, despite widespread calls for experiential and sustainability-focused instruction, there is limited empirical research examining how specific sustainability-centered case studies function as instructional tools within CET curricula.

Integrating RWH into engineering education provides a practical, systems-based framework for sustainability instruction (Ismael et al., 2025). RWH projects engage students in hydrological analysis, structural and site design, water quality management, and socio-political dimensions of infrastructure. As an instructional context, RWH projects offer a systems-based learning environment through which students can connect theoretical

concepts to design decisions, operational constraints, and sustainability trade-offs. Bridging this gap requires pedagogical strategies such as site visits, community-engaged projects, and interdisciplinary integration with environmental science, urban planning, and public policy.

CBL has emerged as a pedagogical approach for narrowing the divide between theory and application by situating learning within authentic engineering contexts. By engaging students in authentic, complex scenarios, CBL enhances analytical reasoning, creativity, and decision-making within real-world constraints. RWH systems are well suited as case studies because they integrate technical design, implementation logistics, regulatory frameworks, and community impact.

This study investigates the integration of RWH–focused case studies into a CET course to examine their role in supporting student learning related to sustainability, systems thinking, and the connection between theory and practice. Using international case studies from the southeastern United States and India, the study employs an exploratory classroom-based approach to assess student perceptions and self-reported learning outcomes associated with case-based instruction. The findings aim to inform instructional design strategies for embedding sustainability-oriented case studies within engineering technology curricula.

The Role of RWH in CET Education

CET education provides a foundation in theoretical knowledge and applied skills essential for sustainable water management. Instruction is supported by foundational texts and peer-reviewed literature that establish core principles while increasingly emphasizing applied problem solving. Despite these resources, many programs emphasize theory over experiential learning. A nationwide survey of 158 faculty teaching water-related disciplines reported a strong reliance on self-developed materials due to the effort required to adapt external resources (Wagener et al., 2007). Faculty spent three to five hours preparing for each hour of instruction, even in established courses (Miranda et al., 2021), leading instructors to assemble customized combinations of case studies, applications, and local datasets. This instructional burden limits the consistent integration of authentic, real-world problems into coursework and constrains opportunities for sustained experiential learning.
CBL addresses these challenges by linking theory and practice through real-world engineering problems (Wagener et al., 2010). In engineering contexts, CBL supports student engagement by requiring learners to analyze incomplete information, evaluate trade-offs, and justify design decisions under realistic constraints.

RWH systems are particularly effective for CBL in CET programs. They encompass core technical components: catchment design, filtration, storage, and distribution while addressing broader environmental and policy considerations such as water equity, stormwater management, and climate adaptation (Chanan et al., 2010; Rahman et al., 2014). Real-world RWH case studies allow students to apply theory to both local and global water challenges. These characteristics make RWH case studies particularly effective for examining how students translate theoretical knowledge into applied design and evaluation tasks.

Prior work emphasizes the importance of addressing the full RWH lifecycle, including design, site assessment, performance evaluation, maintenance, and environmental impacts (Leatherman, 2009). Instruction should examine hydrological and ecological effects such as runoff reduction, infiltration, and groundwater recharge (Chathuranika and Ismael, 2025a; Riflan et al., 2022). As a Best Management Practice, RWH supports stormwater control, flood prevention, and water conservation, reinforcing its relevance to modern infrastructure education.

Bringing Sustainability into the Classroom: Integrating RWH Case Studies into CET Education

Applying engineering principles to regional water challenges: A pedagogical case study on RWH in North Carolina (NC), USA

Rooftop RWH systems are widely used in rural and peri-urban Texas and, with proper filtration and disinfection, can meet United States EPA drinking water standards (Stump et al., 2012). Their scalability and cost-effectiveness make them well suited for instructional design exercises, allowing students to evaluate catchment area,

storage capacity, material selection, and treatment requirements within realistic constraints.

This case study examines RWH systems in NC, building on Jones and Hunt (2010). Three sites, Craven, Raleigh, and Kinston were examined using rainfall data collected via tipping bucket rain gauges (Figure 1), with summarized rainfall patterns shown in Figure 2. In Raleigh, a 1400-gallon cistern supplied toilet flushing from June 2005 to January 2008. In Craven, a 3000-gallon cistern supported irrigation (May 2005–August 2006). In Kinston, a 5200-gallon cistern supported vehicle washing (June 2005–August 2006). These cases demonstrate the adaptability of RWH systems and their ability to reduce reliance on conventional water sources. In the course, students used these cases to examine how system size, end use, and rainfall variability influence performance and design decisions.

Figure 1.
Locations of RWH systems experimented by Jones and Hunt (2010) in NC, USA.

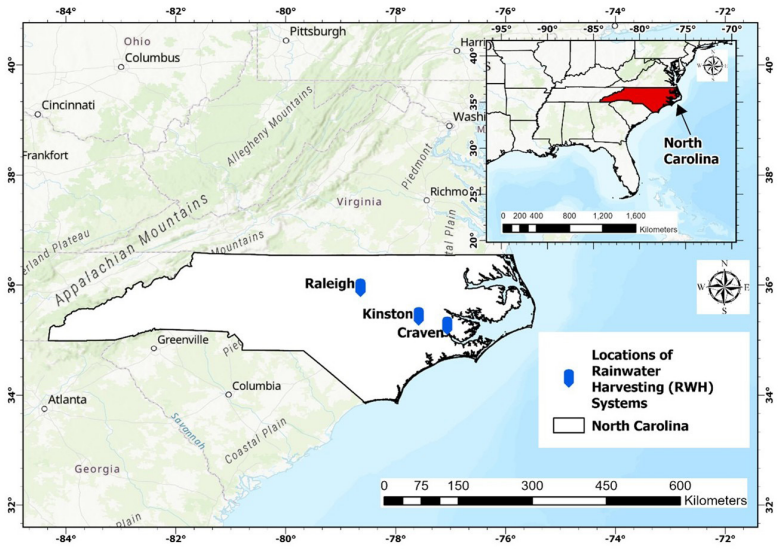
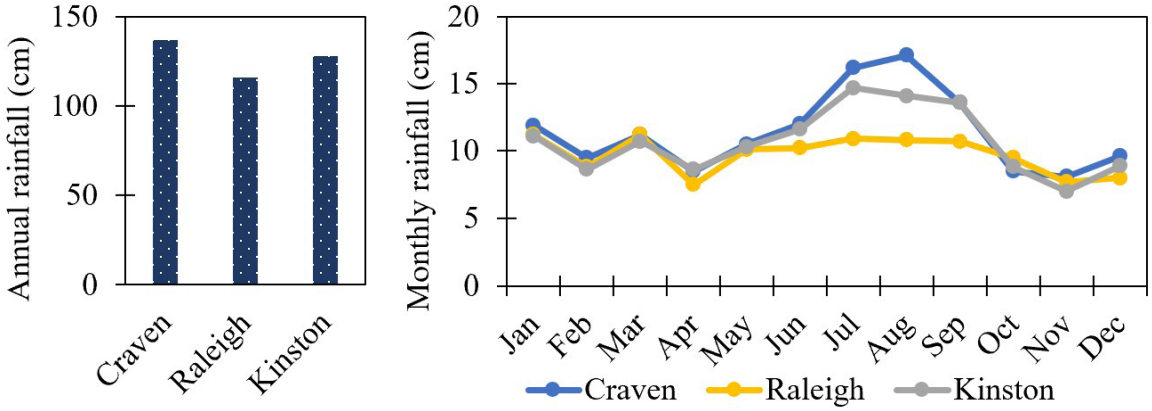


Figure 2.
Annual and monthly average rainfall depths for Craven, Raleigh, and Kinston RWH systems.



Cistern capacity was typically reached when rainfall exceeded 7 cm, a threshold surpassed most months. Long-term performance was evaluated using a simulation model by Coombes and Barry (2007), introducing students to water balance analysis and system modeling.

Results showed that performance depended on rainfall patterns and usage behavior. Small rain barrels frequently overflowed and provided limited irrigation reliability, while larger cisterns performed better, though benefits diminished beyond optimal storage capacity. This emphasizes the importance of proper sizing and demand planning, making the case study well suited for student design and evaluation exercises. Students applied these findings to critique system performance and propose design modifications under varying rainfall and demand scenarios.

This activity supported measurable learning outcomes in hydraulic analysis, data interpretation, and design optimization. Students connected rainfall variability to storage performance, evaluated sizing trade-offs, and justified decisions using quantitative reasoning. The case directly aligns with CET learning objectives, including application of hydraulic principles, system sizing and performance evaluation, simulation tool usage, and interpretation of empirical rainfall data. By analyzing storage optimization, demand variability, lifecycle trade-offs, cost-effectiveness, and system efficiency, students strengthened applied analytical skills, engineering judgment, constructability awareness, and performance-based decision-making under realistic constraints.

RWH in India: A case-based framework for sustainable infrastructure education in CET

India provides a strong context for RWH education due to its long history of decentralized water systems and recent revival efforts. Although RWH was historically widespread, its use declined due to policy shifts, urbanization, and increased groundwater extraction (Agarwal and Narain, 1999; Hoekstra and Mekonnen, 2012).

Community-based restoration efforts demonstrate renewed effectiveness. In Rajasthan's Alwar district, rehabilitated johads raised groundwater levels, reduced energy demands, increased agricultural productivity, and curtailed rural migration (Suutari et al., 2005). Similar outcomes were observed in Galandhar through pond deepening. These cases support CET modules focused on low-cost, culturally relevant infrastructure. These examples were used to prompt student discussion on how low-cost, community-driven infrastructure differs from centralized engineering solutions.

India's RWH practices date back to 300 BCE, with systems such as the Shivaganga and Vieranam tanks illustrating early decentralized management (Datta, 2019); Agarwal and Narain, 1997). Modern RWH technologies range from simple rooftop systems to community-scale installations with filtration and chlorination (Das et al., 2017).

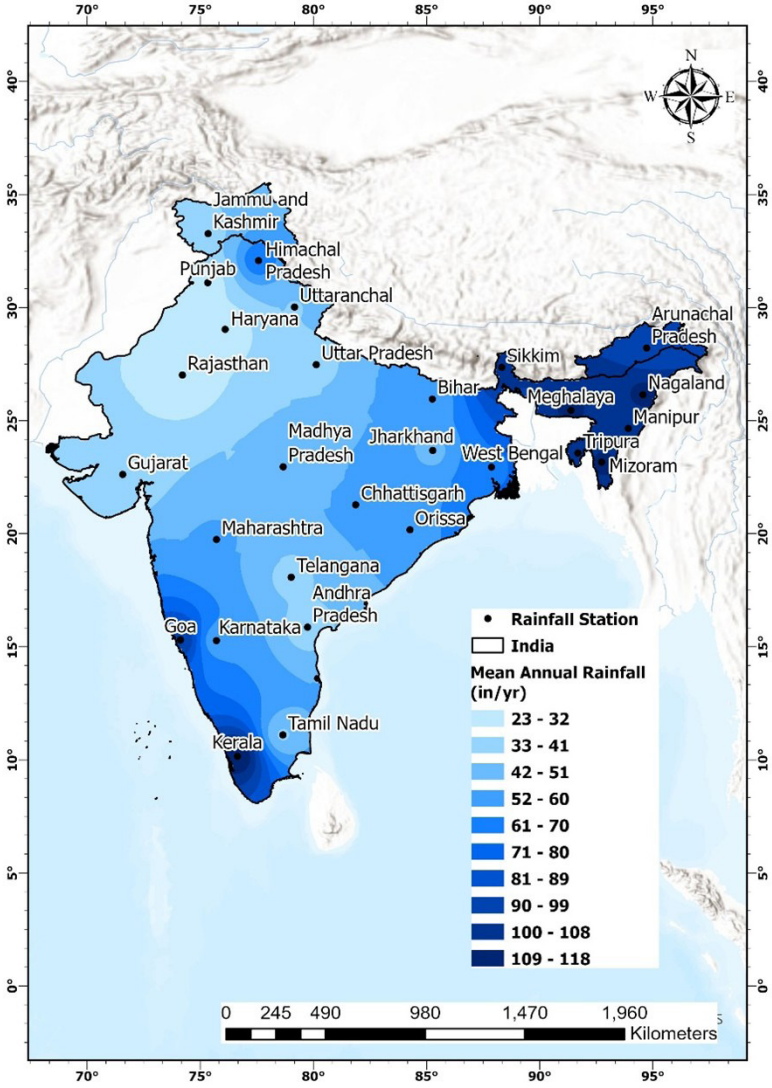
Beyond technical design, Indian RWH systems provide insights into socio-economic and environmental impacts, including community participation, governance, stormwater management, erosion control, and groundwater recharge. Figure 3 presents state-wise rainfall variations relevant to RWH potential assessment.

A Bangalore case study (Manasi and Umamani, 2013) surveyed 120 households and found that 79% installed RWH due to regulatory mandates. Most systems emphasized groundwater recharge, with limited filtration, highlighting policy influence. Concerns over water quality, cost, space constraints, and limited awareness affected adoption. This case exposes students to policy, perception, and maintenance challenges alongside technical design, aligning with findings by Campisano et al. (2017). In the classroom, this case was used to examine how regulatory mandates, public perception, and maintenance practices affect system effectiveness beyond technical design.

Through this analysis, students examined how engineering solutions are shaped by regulatory frameworks, economic constraints, community behavior, and governance structures. The Bangalore case extended technical evaluation to include regulatory mandates, public perception, groundwater policies, and maintenance practices influencing long-term system performance. This integrated perspective reinforced CET learning

outcomes related to sustainability assessment, stakeholder engagement, ethical responsibility, and the alignment of technical design with policy and community contexts. By evaluating both engineered components and institutional frameworks, students moved beyond purely technical analysis to develop a holistic understanding of socio-technical infrastructure systems.

Figure 3.
Average annual rainfall depths of the states in India (Rakhecha, 2016).



Classroom experiment conducted using RWH systems to enhance CBL in engineering education

In CET 458: Managing the Climate Crisis, offered by the Engineering Technology Department at Old Dominion University (Norfolk, VA), two international RWH case studies from North Carolina, USA, and Bangalore, India (pages 26-29) were integrated into a class of nine students (n = 9) to examine the role of CBL in supporting understanding of sustainable engineering practices. As a single-course cohort, the small sample size limits statistical generalizability. Accordingly, findings are exploratory and descriptive, intended to assess pedagogical feasibility and depth of engagement within a specific instructional context rather than establish broad causal claims.

The NC case study by Matthew P. Jones and William F. Hunt assessed RWH performance in Raleigh, Craven County, and Kinston, concluding that mid-sized cisterns (~1800 L) were the most cost-effective when paired with consistent water use, and that public education was essential for adoption and effectiveness. The Bangalore case study by S. Manasi and K. S. Umamani examined large-scale, mandate-driven RWH implementation, finding that more than 25,000 households adopted systems primarily for groundwater recharge due to government policy, public campaigns, and awareness efforts.

Among participants, 56% were seniors and 44% juniors. Age distribution was 20–25 (33.33%), 26–30 (22.22%), 31–35 (33.33%), and above 35 (11.11%). When ranking preferred learning approaches for real-world engineering problems, experiential learning received the highest proportion of first-rank preferences (22.22%), followed by CBL and problem-based learning (PBL), tied at Rank 2 and 3 (21.69% each). Lecture-based learning accounted for 12.70% of preference scores, while discussion-based and self-directed learning received 11.64% and 10.05%, respectively.

Figure 4 presents student rankings of effective learning methods. CBL and PBL were most frequently ranked first (33.33% each) and consistently placed within the top three. Experiential learning was also rated favorably, with 66.66% ranking it second or third. Lecture-based learning was generally ranked lower, with over half placing it fifth or sixth, while self-directed learning received the least support, with 55.56% ranking it last, followed closely by discussion-based learning. Given the small sample size, these findings reflect student perceptions

within a single course context and are intended to inform instructional design rather than provide statistically generalizable results.

Figure 4.
Student rankings of learning approaches for understanding real-world engineering problems, reported as percentage distributions across ranking positions (Rank 1 = most preferred; Rank 6 = least preferred).

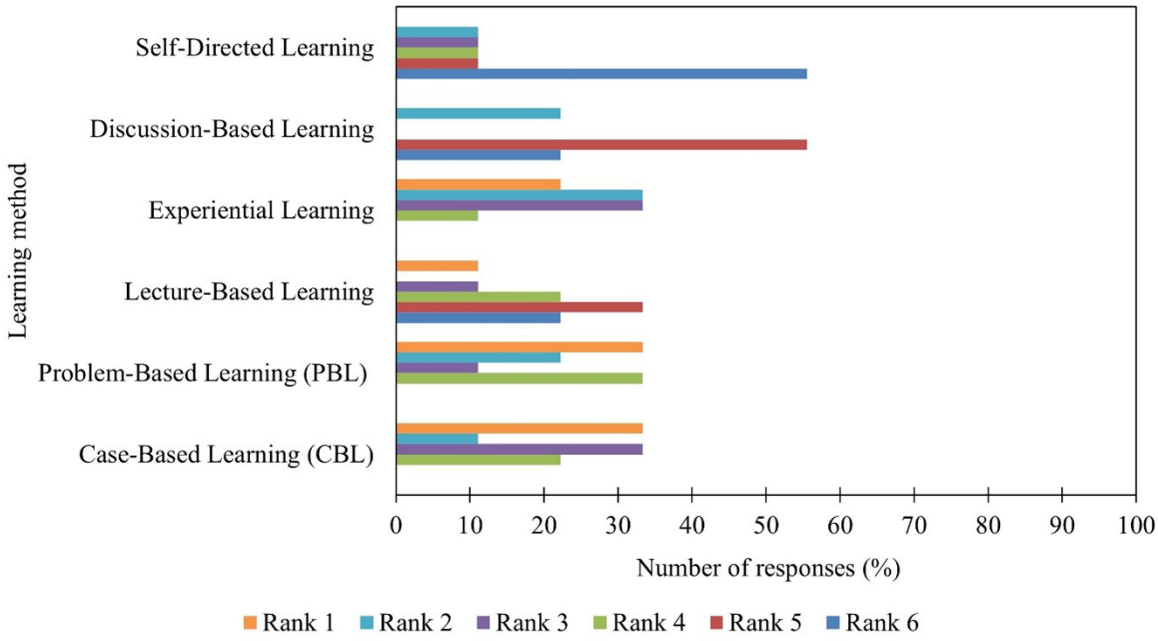
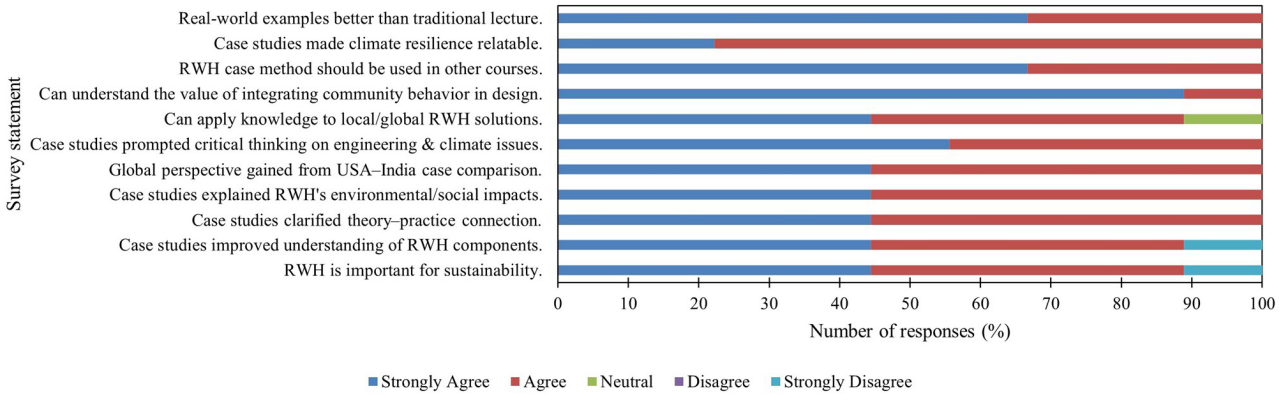


Figure 5 summarizes student attitudes toward integrating RWH case studies into CET education. Post-lesson survey results showed strong support for both RWH and the case-based approach. A total of 88.88% agreed or strongly agreed that RWH is important for a sustainable future (44.44% strongly agreed; 44.44% agreed). All students agreed that the case studies improved their understanding of RWH system components and functions (22.22% strongly agreed; 77.78% agreed), and 88.88% reported improved understanding of the link between theory and real-world application.

Figure 5.
Student responses to post-lesson survey statements assessing perceptions of learning, relevance, and application of RWH case studies within a CET course.



Understanding of environmental and social implications was strong, with 44.44% strongly agreeing and the remainder agreeing. Regarding global awareness, 44.44% strongly agreed that comparing United States and Indian case studies broadened their perspective on international water challenges. Notably, 55.56% strongly agreed that the case studies promoted critical thinking about engineers' roles in climate adaptation and water scarcity mitigation.

In terms of application, 88.88% expressed confidence in proposing RWH solutions in local or global contexts (44.44% strongly agreed; 44.44% agreed), while 11.11% were neutral. A substantial 88.89% strongly agreed on the importance of incorporating community behavior and perception into engineering design. All participants indicated support for adopting RWH-focused case-based instruction in other engineering courses (66.67% strongly agreed; 33.33% agreed), and all indicated that real-world case studies were more effective than traditional lectures, reinforcing the value of applied, context-rich instruction in engineering education.

Teaching with Real-World Projects: Educational Implications of RWH Case Studies

Integrating RWH case studies into CET education provides a structured framework for applied learning and problem-solving. Context-specific examples span diverse geographic and infrastructural settings, progressing from basic household systems to advanced modular designs incorporating automation, filtration, and treatment technologies (Chanan et al., 2007). This scaffolded approach reinforces system mechanics while introducing urban and industrial water management applications. Beyond content familiarity, students develop competencies in applied problem-solving, systems integration, lifecycle evaluation, and socio-technical analysis, aligning with core CET objectives and preparation for sustainable infrastructure practice.

Beyond technical skills, RWH case studies expose students to economic considerations such as capital costs, lifecycle performance, and scalability (Severis et al., 2019), fostering holistic design perspectives that balance performance, affordability, and contextual constraints. They also integrate social and political dimensions, allowing students to examine how community acceptance, stakeholder engagement, and government policy influence infrastructure success. Regional and international examples highlight improvements in public health, water security, and community empowerment, prompting discussion of ethical considerations and inclusive design. Environmental impacts further expand learning through assessment of groundwater recharge, stormwater mitigation, erosion control, and urban hydrology, supporting systems thinking and examination of interactions between engineered and natural systems (Thompson et al., 2012; Chathuranika and Ismael, 2025b).

RWH case studies introduce real-world challenges such as maintenance limitations, system underperformance, and user non-compliance into project-based learning activities. Emphasis on sustainable design, monitoring, and long-term maintenance familiarizes students with the types of constraints encountered in field-based engineering contexts.

Although RWH-focused case studies offer pedagogical advantages, implementation presents practical challenges. Developing context-specific materials requires substantial preparation time, especially when incorporating local rainfall data, simulation tools, or interdisciplinary content. Faculty may encounter resource constraints related to modeling software, field equipment, or institutional support for experiential components. Variability in student backgrounds particularly in mathematics, hydrology, environmental policy, or sustainability concepts may necessitate additional scaffolding for effective engagement with interdisciplinary analysis. Scalability is another consideration: small classes facilitate discussion and applied analysis, whereas larger cohorts may require structured team formats and revised assessments. Mitigation strategies include phased implementation, modular case design, guided worksheets or simulation templates, and cross-departmental collaboration to distribute instructional effort, supporting adoption across diverse institutional contexts.Incorporating both local and international case studies, as implemented in this study, supported student reflection on how engineering solutions vary across climatic, cultural, and regulatory contexts. Exposure to RWH implementation across diverse climates, cultures, and regulatory contexts encourages innovation and cross-cultural competence (Fewkes, 2012). Comparative learning is strengthened through global initiatives: rural systems empha-

size decentralized planning and low-impact technologies, while urban applications focus on stormwater control, potable water augmentation, and climate resilience. Embedding RWH case studies in CET curricula bridges theory and practice while emphasizing adaptability, systems thinking, and the interaction of engineering with policy, culture, and the environment, encouraging students to consider context-sensitive water management approaches in response to climate-related challenges.

Transferability Across Engineering Technology Curricula

Integrating RWH case studies into CET curricula has the potential to support student engagement, technical understanding, and sustainability-related learning. Importantly, this pedagogical model extends beyond civil engineering. Its emphasis on real-world applications, systems thinking, and interdisciplinary collaboration makes it highly adaptable across engineering technology disciplines.

Table 1 presents example undergraduate and graduate courses from engineering technology and related engineering programs to illustrate where RWH case studies could be meaningfully integrated. These courses address hydrology, stormwater management, sustainable development, environmental pollution, and hydraulic modeling. Embedding CBL modules centered on RWH systems provides opportunities to link theoretical concepts with applied water resource management tasks.

Collectively, these courses represent curricular touchpoints where RWH-related concepts align with existing learning objectives. Core courses addressing topics such as climate change, fluid mechanics, watershed processes, and runoff modeling align directly with RWH design and sizing principles. Complementary courses focused on computational tools and modeling support simulation, monitoring, and performance evaluation relevant to RWH system analysis.

Sustainability-focused courses provide environmental and societal context through topics such as resource conservation, low-impact development, and life-cycle analysis. Courses centered on water and wastewater treatment align with RWH end-use considerations, including non-potable reuse, filtration, and integration with urban water infrastructure. Electives addressing climate adaptation and hydrological resilience further reinforce the relevance of RWH systems within sustainability-oriented engineering education.

Together, these courses provide a multidisciplinary context in which RWH case studies could be embedded to support systems-oriented thinking and applied analysis. Even where identical courses are unavailable, equivalent offerings in environmental engineering technology, urban planning, construction management, or water systems operations could incorporate RWH-focused case studies. The approach is conceptually flexible and adaptable across course levels and instructional contexts. Because transferability was not empirically evaluated in this study, these observations are presented as instructional considerations rather than demonstrated outcomes.

Future research should expand implementation while incorporating hands-on and simulation-based activities. Next steps include student-led RWH design projects using local rainfall data, cost analysis, lifecycle modeling, and field components such as site assessments or community partnerships. Interdisciplinary collaboration with urban planning, environmental science, and public policy can further enhance socio-technical learning. Larger, longitudinal, multi-course or multi-institutional studies incorporating objective performance measures and systems-thinking assessments alongside perception surveys are needed to transition RWH case studies from exploratory modules to scalable, research-informed instructional models.

Table 1.
Example courses from a single institution illustrating where RWH-related case studies conceptually align with existing learning objectives.

#	Course Title
1	Introduction to Land Development
2	Water Resources Engineering
3	Computer Applications in Hydraulic Engineering
4	Hydraulics and Water Resources
5	Environmental Pollution and Control
6	Sustainable Building Practices
7	Hydrology and Drainage
8	Resilience and Sustainability
9	Managing the Climate Crisis
10	Urban Stormwater Hydrology
11	Water Distribution & Wastewater Collection System Design
12	Water and Wastewater Treatment
13	Pollution Prevention and Green Engineering
14	Adaptation to Sea Level Rise
15	Sustainable Development
16	Managing the Climate Crisis
17	Introduction to Coastal Engineering
18	Water Quality Management
19	Water Quality Modeling
20	Water Resources Processes and Analysis Methods

Conclusions

Integrating RWH case studies into CET education provides an applied instructional context for engaging students with climate change, urbanization, and global water scarcity. As a cost-effective and environmentally relevant infrastructure strategy, RWH offers a practical bridge between theoretical concepts and real-world engineering applications. Case studies from NC, USA, and Bangalore, India exposed students to diverse system designs, regional constraints, and context-specific considerations, supporting reflection on technical, environmental, and socio-political dimensions of water infrastructure.

Findings from this exploratory implementation indicate that CBL enhanced student engagement with sustainability-oriented engineering concepts and strengthened connections between theory and practice. Through analysis of real-world RWH systems, students addressed modeling, design, environmental impacts, and socio-political factors in infrastructure planning. Feedback reflected positive perceptions, reported gains in understanding RWH components, and preference for applied learning over lectures. However, the small sample size (n = 9), single-institution context, and reliance on perception-based surveys limit generalizability and conclusions regarding objective learning gains. Results should therefore be interpreted as preliminary evidence of feasibility rather than definitive validation.

Embedding RWH-focused case studies into CET curricula represents a promising instructional approach for aligning engineering education with sustainability-related challenges. By emphasizing applied analysis, interdisciplinary considerations, and context-sensitive design, this model may support student engagement with

sustainable water management concepts across a range of engineering technology courses. Future work should examine RWH-based instruction through hands-on projects, simulation tools, interdisciplinary collaboration, and longitudinal assessment to better understand its educational impact across diverse instructional contexts.

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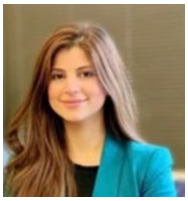

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Engineering and Sensemaking in Elementary: How Materials Mediate Sensemaking Opportunities

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Abstract

Engineering instruction is increasingly integrated into the elementary classroom as a means of supporting science instruction. Central to engineering activities is students' engagement with materials, yet limited research has examined how specific materials shape sensemaking opportunities during learning. Drawing on distributed cognition and sociomaterial perspectives, this study investigates how materials function as mediators of scientific sensemaking in an elementary engineering classroom.

This exploratory case study took place in a fourth-grade classroom at a public K–5 engineering magnet school. Students participated in a design-based makerspace unit focused on electricity and circuits. The analysis centers on an activity in which pairs of students tested the conductivity of various materials using a simple circuit. Audio and video data of students engaging with a materials exploration activity were collected and analyzed to examine sociomaterial interactions, with particular attention to moments that afforded opportunities for sensemaking.

Findings suggest that materials mediated sensemaking in three distinct ways: reinforcing existing scientific knowledge, challenging students' ideas through material complexity, and disrupting procedural testing routines through novel cases. These findings highlight the importance of material selection and task design in engineering instruction. By intentionally incorporating materials that vary in familiarity, complexity, and novelty, educators can create learning environments that sustain opportunities for scientific sensemaking. This study contributes to a more nuanced understanding of how materials actively shape learning processes in elementary engineering contexts.

Keywords: Elementary Engineering, Sensemaking, Sociomateriality, Distributed Cognition

Introduction

Engineering instruction is becoming increasingly more prominent in elementary classrooms as an avenue for promoting deeper science learning (Weng et al., 2023; Levy & Moore Mensah, 2021). This work is supported by frameworks across the two domains that emphasize learning through design, material engagement, and problem solving (*STEL*; ITEEA, 2020; NRC, 2012). These frameworks position learning as an active process grounded in interaction with materials, tools, and systems rather than simply obtaining new knowledge. This shift in focus requires rethinking how learning and cognition are conceptualized in the classroom. Rather than viewing learning as an internal process that occurs solely within an individual, it can be understood as distributed across learners, the environment, and the materials with which they interact (Rogers, 2006). From this perspective, knowledge is constructed through engagement with the world, positioning materials and the environment as essential components of the learning system (Wilson, 2002). This distributed view of cognition is further supported by sociomaterial perspectives on learning, which emphasize that social and material elements are inseparable in the construction of knowledge. From a sociomaterial standpoint, materials are not passive tools used by learners, but active participants that shape what actions are possible, what ideas become salient, and how sensemaking unfolds (Orlikowski, 2007). Together, distributed cognition and sociomateriality provide a framework for examining how interactions among students, materials, and learning environments in the engineering classroom can provide opportunities for scientific sensemaking.

Literature Review

Distributed Cognition

Traditional views of learning often conceptualize cognition as an internal process occurring solely within an individual (Xiaohui, 2024). In contrast, distributed cognition perspectives emphasize that thinking and learning are distributed across individuals, tools, artifacts, and environments (Hutchins, 1995; Rogers, 2006). From this lens, physical materials function as cognitive artifacts that shape the learning environment.

Engineering classrooms provide a clear example of distributed cognition in practice. Engineering provides a context for students to engage deeply with scientific phenomena in real-world applications. They rely on physical materials, representations, and tools to externalize these scientific ideas, test hypotheses, and collaborate with peers. Engagement with the physical world in this way can make abstract scientific concepts tangible, constrain or enable particular actions, and provide feedback that informs students' thinking (Roth, 2001). Through repeated engagement with materials and their environment, students not only develop a deeper understanding of applied concepts but also internalize this learning in a way that enables the functional use of knowledge in other contexts (Chao et al., 2017). This perspective highlights the importance of examining materials and their functional use within a social learning context to better understand the complex system in which learning emerges.

Sociomateriality

Sociomateriality is the view that social and material aspects of a system, in this case the classroom, are deeply entangled, or inseparable. From a sociomateriality standpoint, materials are not passive objects acted upon by learners, but instead they actively shape how learning unfolds through social interactions (Orlikowski, 2007). Artifacts and tools provide novel opportunities for students to socially engage with phenomena both physically and conceptually (Danish et al., 2020). While materials play a crucial role in the learning process, it is essential to recognize the social elements that surround material interactions as well. When students are provided opportunities to communicate throughout the learning process, they develop a stronger conceptual understanding of scientific concepts (Chusinkunawut et al., 2021). A sociomateriality lens recognizes the entangled practices of material engagement and social interaction present in the engineering classroom as students apply scientific knowledge to solve real-world problems (Kumpulainen & Kajamaa, 2020).

Sociomateriality and Engineering Education

There is a growing body of literature that examines the impact of engineering education on student learning in the elementary classroom (Ehsan et al., 2023). Integrated engineering instruction supports students in building scientific knowledge (Schnittka & Bell, 2011; Fortus et al., 2004) through authentic learning experiences that provide students opportunities to make meaningful connections between content learning and real-world applications (Firdaus & Rahayu, 2019). This approach, which mimics practices of real-world scientists and engineers promotes scientific sensemaking, which can be defined as the process of actively trying to figure out how the world works (National Science Teacher Association [NSTA], 2025). With sensemaking at the heart of science education, engineering in the elementary classroom provides a promising context for supporting distributed sensemaking in science education.

A defining feature of engineering education is its emphasis on designing real-world solutions through the application of math and science (ABET, 2024). In engineering classrooms, materials function as cognitive artifacts that shape how students engage with scientific ideas, guide problem-solving processes, and support the construction and development of knowledge (Hutchins, 1995). Through engagement in design challenges situated in real-world contexts, students apply scientific knowledge while working directly with and through materials (Roth, 2001) as they encounter constraints and design failures that cause them to revise their thinking (Long et al., 2020). Integrated science and engineering activities shift the focus of learning from receiving information to making sense of and using scientific knowledge to solve problems, positioning materials as central to understanding scientific phenomena.

Despite growing interest in engineering education and material-rich learning environments, there is limited empirical research examining how materials mediate sensemaking in elementary engineering classrooms. Few studies provide fine-grained analyses of micro interactions among students, materials, and tasks, particularly at the elementary level. Additionally, there is limited attention to how different types of materials afford different kinds of sensemaking opportunities. This study examines how materials mediate sensemaking opportunities in an elementary engineering classroom. Drawing on distributed cognition and sociomaterial perspectives, this study focuses on students' interactions with specific materials as they explore electrical conductivity within design-based context. By attending to the role that materials play in the learning activity as mediators of sensemaking, this study contributes to a more nuanced understanding of the epistemic role of materials in elementary engineering and science learning.

Methodology

Study Design

This study follows a single-embedded exploratory case study design (Yin, 2014) to investigate how materials mediate sensemaking opportunities in the elementary engineering classroom. This case is bound by a single class of fourth-grade students participating in a design-based instructional unit with pairs of students serving as embedded units of analysis (see Figure 1). Student pairs were analyzed as embedded units within the classroom to examine interactions among students, materials, and the engineering design task.

Context and Setting

This case study takes place in a public K-5 magnet school in a large urban school district in the southeastern United States. Mae Jemison Elementary (pseudonym) was purposefully selected due to its magnet focus on engineering. To examine the connection between engineering design and scientific sensemaking, it was important to select a school where teachers consistently teach a science curriculum. At Mae Jemison Elementary, classroom teachers provide science instruction in rotation with social studies throughout the school year. Students then rotate through the makerspace to engage in engineering design challenges aligned with the science content. This positions learning in the makerspace as complementary to classroom instruction, providing opportunities for further sensemaking with scientific phenomena.

Participants

This case study examines Ms. Ochoa's 4th-grade classroom as they engaged in an engineering design unit in the makerspace with Ms. Jackson (both pseudonyms). Ms. Jackson serves as the STEM specialist in the school's makerspace, working with 4th- and 5th-grade students. Ms. Ochoa's classroom consists of 18 students, 12 of whom had parental consent to participate in this study. Participating students engaged in their typical makerspace unit titled "Light up the Night," an adapted lesson from the Engineering is Elementary curriculum (Hester & Cunningham, 2007). Students were divided among three table groups, working in pairs to use what they had learned about electricity and circuits to engineer a light display for a Winter Lights Festival.

Data Collection and Analysis

This study examines one learning activity from a 6-day unit, in which students were tasked with exploring a variety of materials to test conductivity within a simple circuit. Pairs of students were provided with materials to create a simple circuit shown in Figure 2. Students then tested a variety of materials to determine whether each was an insulator or a conductor by observing how it interacted with the circuit. Specific materials are described later in the findings.

Data collection included audio and video recordings of the learning activity and classroom field notes. Recordings were transcribed using a digital transcription tool and reviewed by the researcher to ensure accuracy. Once recordings were transcribed and clipped to only capture the material exploration activity, key data points were extracted from the video data to capture the sociomaterial interactions, including timestamps, student dialogue, materials, and material interactions. This data was then organized into a table and segmented to support in-depth analysis of the sociomaterial interactions. A sample data table is provided in Table 1. Segments

Figure 1.
Embedded case study diagram.

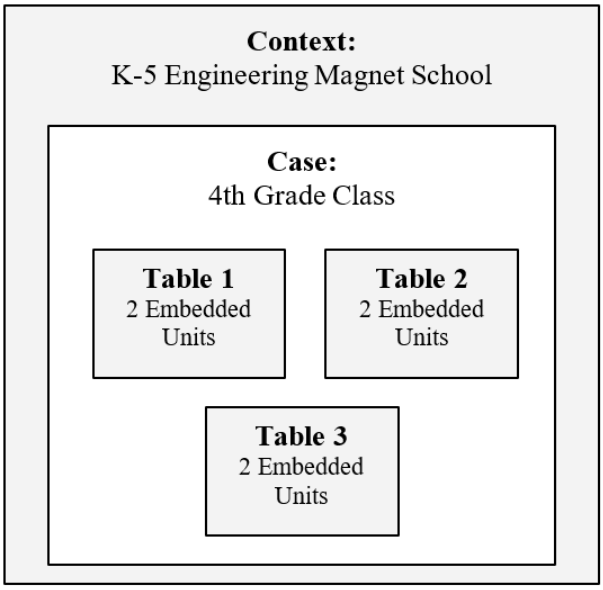
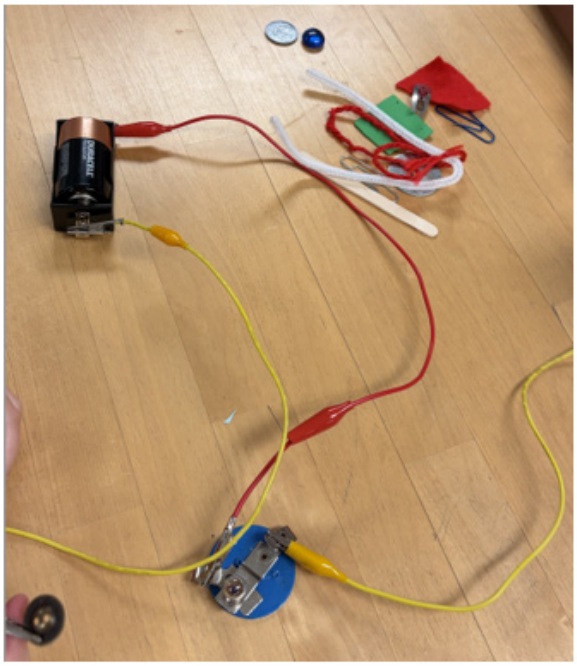


Figure 2.
Circuit materials included three alligator wires, a D battery. battery housing, a small light bulb, and light bulb housing.



were bound by an interaction with a single material. For example, a segment may begin with a student picking up a wooden craft stick to discuss its characteristics and end with the group deciding it is not a viable material for conducting electricity in a circuit. These smaller segments allow for closer examination of the social and material interactions surrounding each material, revealing sensemaking opportunities afforded or constrained by it.

Table 1.
Sample Audio and Video Transcript

Speaker	Timestamp	Talk	Material	Action
Student D	01:22	Let's try again.	Binder clip, Circuit	
Student D	01:25	You do it.		Hands second alligator wire to the partner
Student A	01:31	Okay, 3-2-1...	Alligator wire, Binder clip	Clip the wire to the other handle of the binder clip
Student A	01:32	Yes!	Binder clip, Circuit	Light lights up

To center the active role of materials, segments were organized by material to analyze material interactions and sensemaking opportunities across groups. The data were then analyzed for sensemaking indicators utilizing a sensemaking rubric drafted from the NSTA attributes of sensemaking framework (NSTA, 2025). This framework defines sensemaking in four parts: engaging with natural phenomena, utilizing science and engineering practices, students sharing ideas and prior knowledge, and connecting those ideas to science concepts and language.

These codes were used to note opportunities for sensemaking evident within the material interaction, and descriptive analysis was used to document social and material interactions. It is important to note that the presence of a sensemaking indicator does not signify a moment of high-quality sensemaking, but instead recognizes an opportunity where sensemaking has begun to emerge. For example, when a student states, “I wonder why this material didn’t work,” it demonstrates basic sensemaking through asking questions and expressing curiosity. However, this does not indicate a high-quality example of sensemaking but rather an opportunity where sensemaking may emerge.

Findings

Sensemaking Opportunities in Material-Driven Activities

As students engage with materials in the context of engineering design, they are afforded opportunities to engage in sensemaking through social and material interactions. By centering materials and their mediating role in the learning activity, it is evident that different materials afford unique opportunities for sensemaking. In this case, materials mediated sensemaking in three ways: (1) providing evidence to reinforce existing knowledge, (2) challenging existing ideas through material complexity, and (3) prompting further investigation through novel cases.

Reinforcing Scientific Knowledge

A prominent pattern across students’ material interactions was the use of materials to reinforce or confirm existing understandings about electrical circuitry. Rather than prompting students to generate new explanations, many of the materials students encountered supported sensemaking by validating prior knowledge. These materials positioned students to make predictions before testing and to rely on previously learned ideas about conductivity when reasoning about whether the circuit would be completed. In this way, materials functioned as epistemic resources that confirmed students’ expectations and stabilized their understanding of the phenomenon.

For example, students frequently selected familiar metal objects, such as washers or paper clips, and justified their choices by stating, “If it’s metal, I definitely know it’s going to work,” or, “It’s not metal, so it’s not gonna work.” These early assumptions about metal being a conductor were continuously confirmed as students tested various metal and non-metal objects. Through repeated testing, students increasingly articulated that it was the material property, metal, rather than the shape or specific object type, that allowed electrical current to flow. The material behavior helped students align their observations with established scientific ideas about conductivity. Table 2 showcases interactions of three student pairs as they engaged with materials that reinforced their understanding of metal as a conductor of electricity.

Table 2.
Reinforcing Scientific Knowledge Examples

Group	Student	Timestamp	Talk	Material	Action
Group 1	Ada	07:24	Okay, a metal paper clip	metal paper clip, circuit	
	Grace	07:28	It's going to work!	metal paper clip, circuit	Student clips alligator wires to a paper clip
					Light lights up
Group 2	Marie	06:48	Wait, I really want to try this washer down here	Washer	Grabbing from the baggie of materials
	Katie	06:50	I think it will work		
	Marie	06:53	because it's metal	Washer, circuit	
	Katie	06:56	This big reveal		Connects wires to the washer
	Marie	07:01	It turned on!		Light lights up
Group 3	Eli	02:03	I feel like this will work	Washer, circuit	
	Mitchell	02:24	Alright. Okay...		Connects the washer to the circuit
	Mitchell	02:24	It lights up! What is it?	Washer, circuit	Light lights up
	Eli	02:28	I don't know. A metal something. A metal ring?		

As the activity progressed, however, the confirmatory role of these materials became increasingly apparent. Students continued to test metal objects, but these interactions were often rapid and procedural, serving primarily as a means of verification rather than exploration. Once students felt confident that their reasoning had been validated, testing metal materials no longer prompted additional sensemaking or reconsideration of ideas. Instead, these materials functioned to solidify understanding, signaling to students that further investigation was unnecessary. This pattern suggests that while materials can play a productive role in reinforcing scientific understanding, their epistemic function may shift over time from supporting sensemaking to confirming conclusions, depending on students' levels of certainty.

Challenging Existing Ideas through Material Complexity

In contrast to materials that confirm existing understanding, some material interactions challenged students' existing ideas about conductivity by introducing material complexity. These materials enhanced scientific understanding by disrupting simple classifications and requiring students to attend to multiple components within a single object. Complex materials in this context consisted of objects composed of more than one material or component, such as pipe cleaners (metal wire wrapped in fuzzy fibers) or binder clips (steel body with wire handles). When students engaged with these materials, they were no longer able to rely on a single material category to predict conductivity. Instead, students had to consider how different components interact within the circuit. This complexity prompted students to verbalize predictions and reasoning as they observed how the circuit responded. For example, students across multiple groups shared reasoning such as, "I think it will work because it has metal in there," or "I think it's because of the metal inside."

These materials frequently led students to test conductivity multiple times, adjusting how the object was positioned or which component was connected to the alligator wires. As students observed partial or inconsistent functionality within the circuit, they explored how certain configurations worked while others did not. In these moments, materials supported sensemaking by challenging students' existing ideas and prompting them to refine their understanding of conductivity as dependent on material properties and system configuration, rather than on the object as a whole. In the example below, students at Table 1 discuss circuit configuration as they explore whether the binder clip is a conductor or an insulator. In this moment, students slowed down their procedural process of connecting each material to the circuit in order to discuss material components and system configurations. This provided an opportunity to make sense of electricity flow through different components of the material and better understand its conductivity as dependent on material properties and circuit configurations.

Table 3.
Challenging Existing Ideas through Material Complexity Examples

Speaker	Timestamp	Talk	Material	Action
Ada	03:25	So first I feel like we should do two [tests]. So first we should do one clipped onto the middle, one clipped on it down here [the black part]. And then do another one where we clipped on here and one clipped on here.	Binder clip	Holding the binder clip, pointing to the two components.
Ada	03:35	So the first one would be...	Binder clip, circuit	Clips one wire to the black part of the binder clip and the other to the metal clamp.
Ada	03:53	This one doesn't. It doesn't work.		Circuit doesn't light up.
Grace	03:56	It works a little bit! It was working a little bit.		Light dims and brightens.
Ada	03:50	I don't think it was clamped on correctly. Yeah, it works.	Binder clip, circuit	Readjusting the wires.
Grace	04:02	But only a little bit. Wait, maybe it has to be...	Binder clip, circuit	Adjusts the wires to both connect to the wire handle.
Ada	04:09	Oh yeah! That one works now.		

Prompting Investigation through Novel Cases

Across groups, moments of disruption emerged when students encountered novel cases that did not neatly align with established patterns. As students progressed through the investigation, they became increasingly efficient in their testing, quickly categorizing materials based on previously confirmed findings, often surrounding confirmed ideas that metal is a conductor and plastic is an insulator. This flow was interrupted when students encountered materials that introduced uncertainty and did not fit into their existing framework. Novel cases required students to draw on prior knowledge while also making predictions about materials whose properties were less familiar or more difficult to test.

One example, shown in Table 4, occurred when students engaged with a glass bead. The bead presented a dual challenge: it introduced a new material type (glass) that students were unsure how to classify, and its shape made it difficult to connect the alligator clips in a straightforward way. Unlike flat or elongated objects, the round bead did not afford easy attachment, disrupting students' typical testing routines.

As a result, students were prompted to slow down and engage more deeply with the material, providing an opportunity for sensemaking. Rather than quickly testing and confirming expectations, students had to brainstorm alternative strategies for determining conductivity, negotiate how to physically interact with the material, and reason through whether difficulties in testing were due to the material itself or the testing setup. In this way, the glass bead functioned as an epistemically complex material, prompting investigation by resisting easy categorization and procedural testing. These moments of uncertainty created space for students to re-engage in explanation-building and collaborative problem-solving, highlighting how novel material cases can reinvigorate sensemaking within an otherwise confirmatory investigation.

Table 4.
Prompting Investigation through Novel Cases Examples

Speaker	Timestamp	Talk	Material	Action
Marie	10:11	Okay. Wait. So now I feel like I want to try this little marble.	Glass bead	Picks up the glass bead.
Katie	10:15	Cool. It looks like a gem.		
Marie	10:19	Yeah		
Katie	10:32	Okay, there, hook it up.	Glass bead, circuit	
Marie	10:37	*giggles* sorry.	Glass bead	Falls onto the table.
Marie	10:40	Here, maybe one of us should hold it.	Glass bead, alligator wires	Having trouble connecting alligator clip to the glass bead
Marie	10:44	Okay. What if we just touched it with both of them? Cause it's gonna... it better go through. Okay.		
Katie	10:51	Nothing happened.	Glass bead, circuit	Light doesn't light up.
Marie	10:51	Nope.	Engineering Notebook	Writing a glass bead as an insulator.

Discussion of Findings

Different materials mediated sensemaking in distinct ways, shaping the kinds of sensemaking opportunities students were provided within the activity. This supports prior findings that materials play an active role in the learning process (Beltagui et al., 2023) and warrant explicit consideration in the design of learning activities. Providing students opportunities to engage with diverse materials that confirm scientific ideas, challenge existing misconceptions, and provoke further inquiry can provide a high-quality learning environment that promotes sensemaking and knowledge development.

The epistemic role of materials can shift over the course of an activity. Initially, material interactions that confirm scientific ideas play an important role in supporting students' understanding and building confidence in their reasoning. However, as materials repeatedly produce expected outcomes, their capacity to prompt further

sensemaking diminishes. When students encounter no uncertainty or surprise, material engagement becomes confirmatory rather than generative, limiting opportunities for reconsideration or deeper explanation. This suggests that while materials are valuable epistemic tools, their effectiveness is time-bound, and novelty affects how students engage with them.

To sustain sensemaking, students must engage with materials that not only validate ideas but also introduce productive tension by challenging existing understandings and inviting further exploration. This can be achieved through material complexity and novelty. This is not to say that materials themselves possess epistemic autonomy within an activity, but that the features and functionality of materials can impact the opportunities provided to communicate scientific ideas and test knowledge in authentic contexts.

Together, these findings suggest that when developing science and engineering activities, it is important to consider the role of materials in the learning environment. By providing students opportunities to engage with novel and complex materials they afforded opportunities to engage in sensemaking by challenges existing ideas, furthering their knowledge, and problem solving solutions. While simply providing students with metal, wood, and a pom pom ball could have provided students the knowledge to draw conclusions about conductivity, it lacks opportunities for students to strengthen and challenge that understanding. Acknowledging the role of materials in shaping sensemaking opportunities can shift instruction in science and engineering from confirmatory science explorations to sensemaking opportunities.

Although this study examines a single bounded case, it extends prior research on the role of materials in affording sensemaking opportunities within engineering design activities. Building on sociomaterial perspectives that center the entanglement of social interaction, task design, and material engagement in classroom learning (Johri, 2011), these findings highlight how sensemaking emerges through students' interactions with both peers and materials. Further research is needed to expand on these findings and to better understand how educators can intentionally incorporate diverse materials into instruction in ways that sustain opportunities for sensemaking. Together, these findings underscore the need for instructional designs that move beyond the mere inclusion of materials toward a more intentional consideration of how material properties and configurations shape students' sensemaking.

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Advancing STEM - Project Approach in Learning (PAL)

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Abstract

Despite the global consensus on the importance of STEM education, a significant gap remains between abstract pedagogical goals and effective classroom implementation. To address this urgent need, this paper presents the "Project Approach in Learning" (PAL)—a comprehensive framework designed to systematically enhance technology and engineering pedagogy. Grounded in constructivist and experiential learning theories, PAL offers a robust blueprint for creating engaging, student-centered learning experiences.

The PAL model is organized into three core components. First, Project Planning defines the educational architecture through five distinguishing features that ensure a meaningful learning journey: the project is Problem-Based, grounded in a Scenario-Leading context, requires Knowledge Connectedness across disciplines, promotes deep Exploration & Elaboration, and culminates in a Tangible Production. Second, Lesson Arrangement structures classroom delivery using a narrative-driven "Three-Act Structure" (Setup, Confrontation, Resolution). The critical "Setup" phase is guided by the INTRO method—capturing Interest, identifying Needs, establishing the Title and Revision points, and clarifying Objectives—to ensure a purposeful lesson launch. Third, Instruction Strategy weaves these elements together using the "4Cs Strategy." Inspired by Alister Jones (2007), this includes Connectedness, Coherence, and Continuity, with the addition of a unique fourth C—Convergence—to ensure all activities are purposefully aligned toward tangible outcomes and assessment.

This paper dissects each component of the PAL framework, demonstrating how its integrated structure serves as a scalable, theoretically sound approach for nurturing the problem-solving and innovation skills essential for the future of STEM.

Keywords: STEM Education, Project Approach in Learning (PAL), Curriculum Design, Instructional Strategy, Project-Based Learning

Introduction

While STEM education has achieved a global consensus as a necessity for future readiness, its pedagogical implementation varies significantly across regions and even among schools within the same city. Among these diverse methods, project-based approaches serve as a common practical core. However, in practice, this often deviates from the original intent of STEM education. Many so-called "STEM projects" are unfortunately reduced to fragmented model-making or toy assembly. This approach fails to effectively cultivate students' ability to integrate interdisciplinary knowledge or solve real-world problems. This practical deviation stems partly from a fundamental issue: the lack of a clear, executable framework to define what constitutes a "high-quality STEM project" and to guide teachers on how to effectively organize and facilitate instruction within a project's scope.

Recognizing these implementation gaps, and drawing upon our decade of experience in K-12 project development and teaching practice, we have refined and developed a pedagogical framework named the "Project Approach in Learning" (PAL). This framework is designed to remedy the guidance gap often found in traditional Project-Based Learning (PBL), which can be difficult to implement due to its open-ended nature. The goal of PAL is to provide educators with a clearly structured and highly practical teaching pathway.

The STEM PAL framework is built upon three pillars: (1) Project Planning, which defines the core characteristics of a quality project to lay a solid foundation; (2) Lesson Arrangement, which introduces an innovative "Three-Act Structure" to guide the effective organization of each lesson; and (3) Instructional Strategies, which reveal how to weave discrete lessons into a coherent project experience. This paper aims to elaborate on the composition, theoretical underpinnings, and originality of the STEM PAL framework, with the objective of offering STEM educators a clear, practical, and academically robust teaching model that addresses the current implementation challenges in STEM education.

Theoretical Foundations

PAL is grounded in a synthesis of established educational theories, translating cognitive and social constructivism into actionable classroom strategies.

Constructivism and Learning by Doing

PAL realizes Piaget's cognitive constructivism (Piaget, 1971) by engaging students in active, hands-on problem solving. Students construct and reorganize schemas by linking prior subject knowledge—such as physics or chemistry—with new project demands. The five elements of project planning require learners to explore, test, and revise ideas. This iterative experimentation with materials and tools reflects Piaget's view that understanding grows through self-initiated interaction with the physical world, particularly when abstract concepts are anchored in concrete operations and real artifacts.

Simultaneously, PAL embodies Vygotsky's social constructivism (Vygotsky, 1978) by making learning inherently collaborative and scaffolded. Projects are embedded in authentic scenarios that demand group investigation and design decisions, encouraging the negotiation of meaning and shared problem-solving among peers. Classroom routines, such as common workshop rules and collective clean-up, alongside shared products displayed on campus, build a community of practice. Within this community, students internalize technical language, social norms, and design standards.

PAL can be positioned as a modern extension of John Dewey's philosophy (Dewey, 1938) because it systematically realizes "learning by doing." Dewey argued that education should begin from learners' real experiences, organized around problematic situations that require inquiry, reflection, and meaningful action. PAL's "Problem-Based" and "Scenario-Leading" principles place students in authentic, ill-defined real-world situations. Students inquire, design, build, and test tangible products. Thus, knowledge is not transmitted but reconstructed through consequential action, deepening Dewey's concept into "learning by doing in authentic, socially relevant projects." This also echoes the views of contemporary Chinese educator Tao Xingzhi, who stated that "learners' learning strategies should be based on the strategies of doing things" (Tao, 2016).

Narrative Structure and Cognition

The lesson design of PAL incorporates Jerome Bruner's theory of narrative (Bruner, 1996) . The "Three-Act Structure" (Setup–Confrontation–Resolution) transforms lessons into a narrative arc. Bruner posited that narrative is a primary mode of thought that helps learners organize experiences and make sense of complexity. PAL's Setup establishes the characters and situation (authentic scenario, user needs), the Confrontation provides complications (technical and design challenges unpacked in "onion-style" blocks), and the Resolution offers closure and reflection. This narrative form helps students "plot" the complex design process into mentally manageable episodes, supporting meaning-making and sustained motivation.

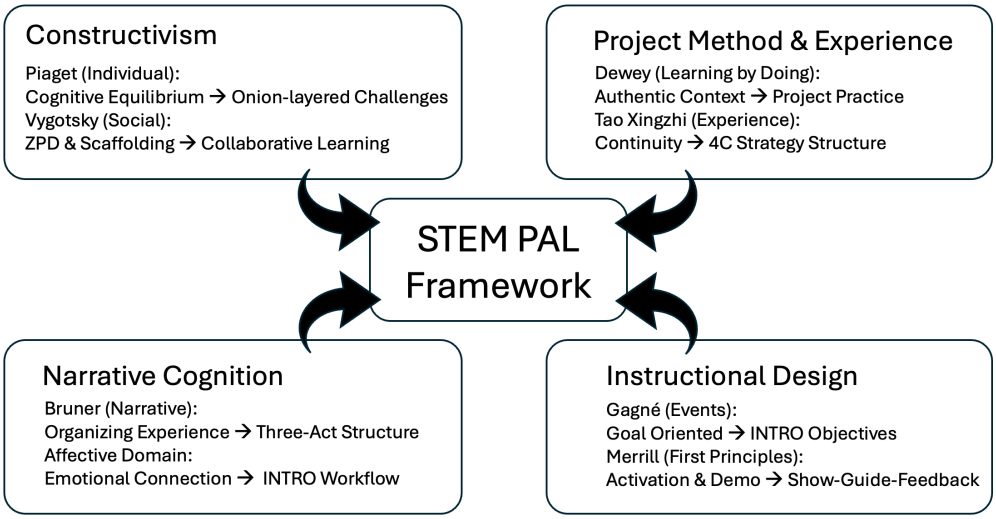
Instructional Design Principles

Pure PBL often assumes that open exploration alone will yield robust learning, but in practice, learners can overlook key concepts, get lost in complexity, or focus on the product over understanding. PAL addresses this by embedding projects in a clear instructional design framework. The INTRO sequence in the Setup phase mirrors Gagné's events of instruction (Gagné, 1985) — gaining attention, informing learners of objectives, stimu-

lating recall, and guiding learning. Furthermore, the framework aligns with Merrill's first principles of instruction (Merrill, 2002): problem-centered tasks, activation of prior knowledge, demonstration, application, and integration. PAL accommodates different learning paces and diversity by synchronizing project progress and adjusting support, aligning with Vygotsky's view that effective instruction is differentiated to learners' varying Zones of Proximal Development (ZPD) (Vygotsky, 1978).

Based on the theories discussed above, the theoretical foundations of the STEM PAL framework are synthesized in Figure 1.

Figure 1.
Integration of Constructivism, Project Method, Narrative Cognition, and Instructional Design Principles in the STEM PAL Framework



The PAL Framework: A Structured Approach from Ideation to Production

Overview: A Three-Pillar Architecture

We believe that PAL, our unique approach to hands-on project learning, can significantly improve learning efficiency and inspire higher-order thinking. The design cycle process for tackling a STEM project problem involves an in-depth investigation and analysis, not just of the problem itself, but of the real problem behind the problem. To ensure all STEM projects align with this vision and meet a high standard of quality, we have distilled the Project Approach in Learning (PAL). This framework is built upon three essential pillars: Project Planning, Lesson Arrangement, and Instructional Strategies.

Within Project Planning, we outline the ideal constitution of a STEM project, which also serves as a metric for educators to validate the quality of their own projects. Lesson Arrangement focuses on guiding educators, especially novice teachers, in conducting a STEM lesson within the scope of a weeks-long project. Finally, to weave all the disparate lessons under a single project together cohesively, we developed our Instructional Strategies.

Pillar I – Project Planning: Designing the Pedagogical Blueprint

Unlike industrial or commercial projects, student projects cannot be completed in a single, continuous session unless they are extracted from the normal timetable and designated as elite, extra-curricular activities. Instead, projects must be divided into several lessons and allocated into discrete, often scattered, timeslots. Consequently, these lessons cannot be topic-driven in the way traditional disciplines are. The pace of these projects is variable, and assessing learning outcomes is far more complex compared to grading questions with simple binary answers.

Drawing from decades of experience in providing teacher support services, we have analyzed various STEM projects and the approaches used to conduct them. We believe that the following five distinctive features are the cornerstones of a good project—one that can fulfill the requirements of enhancing learning efficiency and fostering high-order thinking.

Problem-Based: Defining Authentic and Engaging Problems

Students need to understand why they are undertaking a project. Consider the common practice of "Solar Car" projects. A STEM class of 20 pupils might build their own solar cars under a teacher's supervision. But what happens after the class? Often, there are 20 new artifacts in the rubbish bin. What were these solar cars for? Was the goal to learn a science concept about renewable energy or to get hands-on experience in sustaining our environment? If so, why did the lesson produce 20 pieces of rubbish?

We must make STEM projects more authentic and imbue each creation with meaning. We need to let students know they are solving a valuable problem and creating value for others, not just doing what a teacher tells them to do. Problem-based learning is not merely a slogan; it is a pathway to convincing and meaningful learning. Empathetic engagement is the beauty of PAL, as it opens a path to value education.

In PAL, problems should be discovered by students rather than predefined by teachers. This student-driven discovery can be facilitated using the "Five Rings of Problems" approach: needs, accidents, current situations, difficulties, and challenges. Unlike traditional methods, PAL projects are based on ill-defined problems within specific scenarios, encouraging students to explore and innovate.

Traditional STEM projects are often title-based, such as "Design and make a chair for the elderly to sit on while waiting for buses." Here, the problem is implicit. Such projects run the risk of devolving into production-oriented tasks. One author recalls a Grade 7 woodworking class where every student competed to make the exact same toothbrush rack. Similarly, task-based projects, like building a robot for a competition, can also miss the point. The purpose often becomes merely completing the task without delving deep into the actual problem. A project like "design and make an egg cracker" is title-based if announced as such. Adjusting the tone to "design a device to open eggs efficiently" makes it task-based. This seems to offer more room for creativity, but if a student suggests a giant hammer to smash all eggs at once, it technically fulfills the task while missing the nuance of the real need.

A problem-based project is different. The focus is on the process of students discovering and defining the problem for themselves. We advocate a three-stage design cycle: Planning (identification of problem, investigation of design factors, formulation of design specifications), Design (ideation, idea analysis, formulation of solution), and Realization (tangible production, testing and evaluation).

Scenario-Leading: Crafting Compelling Learning Contexts

PAL suggests using authentic scenarios because it creates a meaningful context for student learning. We advise teachers to develop projects related to students' daily lives and to ensure the scenario is accessible. This allows students to investigate as they see fit, thinking deeply enough to unearth the underlying problem. Disciplines like Geography, History, and Cultural Studies can all contribute to such projects, positioning STEM as a hub of interdisciplinary learning.

For example, in a Grade 9 project to create a Bluetooth speaker, students had to think about the speaker's location, user, and purpose, which drove them to conduct a series of scenario investigations. The final products were designed and manufactured according to different scenario needs. Returning to the egg cracker project: with a scenario-leading approach, we might simply describe the situation: "Fast-food restaurants need to prepare a large number of eggs every morning." Students could then be taken to a fast-food shop to observe the kitchen's operation, interview staff, log data on egg consumption patterns, and analyze recipes. This deep immersion into the scenario is what leads to genuine problem identification.

Knowledge Connectedness: Mapping Essential Concepts and Skills
"Apply what you have learned(學以致用) is a traditional concept, yet many students resist learning abstract concepts like calculus because they see no practical use for them. PAL addresses this by actively connecting different domains of knowledge during the project.

For example, in a VR glasses project, students used ray diagrams from physics to determine the optimal distance between the lens and the phone. This approach not only enables successful project completion but also deepens students' learning experience. Similarly, when teaching Grade 8 students to join acrylic sheets, we guided them to observe the relationships between solutions, solvents, saturated solutions, and crystallization, aligning this knowledge with their science lessons.

Before arranging projects for each school term, we collect teaching schedules from all department chairs. A detailed analysis is carried out to identify learning elements covered in the previous term. These elements are tabulated, and when developing a new project, we undertake a "mapping of learning elements" to ensure the project requires students to apply what they have just learned.

Exploration & Elaboration: Designing Pathways for Inquiry
Unlike a scientific investigation, "exploration" in a STEM project does not necessarily mean repeating experiments to find relationships between phenomena. Instead, it often involves exploring materials and techniques that students have never used before. "Elaboration" is akin to optimization in engineering. We are not seeking a single "truth," but rather the most optimized solution among infinite possibilities. Trade-offs are a key strategy. For instance, students learn that while a larger battery powers a robot longer, its added weight reduces efficiency. Through trade-offs, they find the optimal balance.

Tangible Production: Defining Meaningful Outcomes
In some humanities disciplines, the "product" might be theoretical. In STEM, however, our consensus is to advocate for innovation that leads to something tangible and real. We expect the outcome to be more than just a concept drawing or a written report. Tangible production stresses authentic experience. We have graduates for whom the most vivid memories of their school life are centered on what they have built, with some keeping their project products long after graduation.

Pillar II – Lesson Arrangement: Structuring the Learning Sequence with the Three-Act Framework
Over the last few years, we have conducted numerous lesson observations. We found that even when teachers used the same textbook and conducted the same project, effectiveness varied dramatically. The problem was not the content, but the individual teacher's interpretation and pedagogy. A STEM project lesson is unlike typical classroom teaching; lessons often commence from different points of progress. Therefore, a clear yet flexible arrangement is a must. We deliberately divide a lesson into three parts, adopting terminology from drama: the Three-Act Framework.

Act I - Setup: Launching the Project with the INTRO Method
The first five minutes are crucial. A STEM lesson usually takes place in a workshop where students arrive from various previous lessons, carrying different emotions. It can be difficult for them to settle down. The first five minutes must be used effectively to calm the class and draw their attention. We use the acronym INTRO:

- Interest: This involves motivating students and capturing their attention. We advocate for an "escapement technique." Students often arrive in a relaxed state, lacking the focus required for a structured workshop. Teachers can use physical conditioning for concentration training, such as a routine where students stand at their assigned seats, wait for silence, and salute together. This routine moves them from "indulgence" to focus.
- Needs: Regardless of progress, the class should have a clear objective. It is the teacher's job to persuade students of the need for the current task, giving their work sensible meaning.
- Title: The title reflects the actual mission of the lesson. Instead of a generic topic, a clear, action-oriented title gives students a sense of ownership and anticipation.

- Revision: Since project lessons are scattered, teachers must remind students of the project's progress, bridging the gap between the previous session and the current one to maintain spiral progress.
- Objectives: Outlining all goals ensures the whole class moves in the same direction.

Table 1.
The INTRO Method for Lesson Startup

Component	Description	Purpose
Interest	Capturing attention (e.g., escapement technique)	Motivation & Focus
Needs	Explaining the "why" of the task	Meaning Making
Title	Action-oriented naming	Ownership
Revision	Bridging previous lessons	Spiral Progress
Objectives	Outlining goals	Direction

Act II - Confrontation: The Onion Approach
The main part of the lesson is the developmental stage. We use the term "Confrontation" because handling an authentic design cycle involves confronting numerous challenges. Furthermore, making things with tangible materials requires physical exertion and sustained focus.

When engaging in hands-on activities, our brains can be triggered to release dopamine, a neurotransmitter linked to the reward circuit, learning, and memory (Willis, 2007). This release enhances effectiveness and focus. However, sustained concentration is finite. Therefore, we suggest differentiating a lesson into several blocks, each with mini-challenges corresponding to the project's developmental stage. The duration of each block should be 10-15 minutes, followed by a 5-minute break for consolidation. We call this layered structure the "Onion Approach." These breaks are ideal for utilizing targeted questions to recall experiences from the preceding block, effectively consolidating memory while the brain is primed.

Act III - Resolution: Reflection, Revising, and Reinforcing
Teachers must manage time to retain at least five minutes for the Resolution. We call this the "golden moment." It involves a brief reflection and revision session through questioning. A successful resolution phase indicates an effective lesson. This phase should also include practical tasks such as putting away work and tools and cleaning the workshop, thereby cultivating habits of discipline and responsibility.

Pillar III – Instructional Strategies: The 4Cs Framework
A significant challenge for STEM teachers, particularly in contexts like Hong Kong where workshop availability necessitates fortnightly classes, is maintaining cohesion across lessons separated by significant time gaps. To address this, we developed our Instructional Strategies, an adaptation of the 3Cs proposed by Alister Jones (2007), to which we have added a fourth "C".

Connectedness: Linking Knowledge Across Disciplines
This principle functions as an active instructional strategy. The teacher must deliberately seize every opportunity during a lesson to highlight how knowledge from different disciplines (e.g., science, math, art) is being applied. This active reinforcement helps students build a mental map of interconnected knowledge, transforming abstract concepts into practical tools.

Coherence: Aligning Each Lesson with the Project's Goal
While lessons may focus on different skills or sub-tasks, they must all be framed within the context of the overarching project goal. It is the teacher's responsibility to constantly remind students of the "big picture," explicitly stating where the current lesson fits within the entire project's timeline. This ensures students see each lesson not as an isolated event, but as a meaningful step toward a shared objective.

Continuity: Maintaining Momentum Between Lessons
To bridge time gaps, learning must extend beyond the classroom. This strategy involves providing after-class extension activities and previewing the content of the next lesson. For example, students might be asked to research a specific material at home or observe a related phenomenon in their community. These small tasks maintain learning momentum and are particularly helpful for lower-achieving students, giving them extra time to process information.

Convergence: Focusing on Learning Outcomes and Assessment
The final "C" is Convergence. This strategy focuses all project activities toward tangible learning outcomes and assessment. Teachers must be constantly aware of the key knowledge and skills that will be formally assessed. By adopting a convergence mindset, teachers deliberately highlight and reinforce these important learning points throughout the project, ensuring students build a solid knowledge base to demonstrate their mastery.

Discussion

Positioning PAL as an Enhanced Model of Project-Based Learning

PAL describes in detail how a hands-on project can be conducted in a school environment to enhance learning. PAL is distinct from, but not opposed to, PBL. PAL aligns with PBL in addressing a "Problem" as a means to inspire learning. However, where PBL often focuses on the inquiry process of acquiring knowledge, PAL emphasizes the tangible outcome in solving the problem. PAL suggests an integrated project framework rather than just a pedagogical approach.

Table 2.
Comparison between Traditional PBL and PAL Framework

Feature	Traditional PBL	PAL Framework
Focus	Inquiry Process	Tangible Production & Problem Solving
Structure	Often Open-ended	Structured (Three-Act, 4Cs)
Problem Source	Often Teacher-assigned	Scenario-Leading / Student-discovered
Lesson Flow	Variable	Narrative Arc (Setup-Confrontation-Resolution)

Comparative Analysis with Existing Frameworks

PAL is deeply founded in education theories. The "Onion Confrontation" in the Three-Act structure inherits constructivism from Piaget and Vygotsky. The focus on authentic scenarios and the 4C strategy follows the idea of "Learning by Doing" proposed by Dewey and Tao Xingzhi. The Three-Act structure, especially the INTRO method, coincides with Bruner's narrative cognition. PAL also integrates core principles from instructional design masters like Gagné and Merrill to ensure pedagogical structure and effectiveness.

Implications for Educational Practice and Curriculum Design

PAL is a holistic framework. It not only suggests how to design a STEM project for curriculum planners but also provides a clear flow for conducting a lesson effectively. Most importantly, it bridges the gaps between discontinuous lessons for more effective implementation.

From Practice to Theory: The Genesis of the PAL Framework

Distilled from decades of teaching experience, PAL emerged from the process of figuring out what technology means for education and patching up concepts that sound good in theory but are difficult to realize. We acknowledge that the iterative design process is a "wicked path," but it is realistic and close to social situations. The value of going through such projects is immense. This is a bottom-up process; the theories cited are tools to explain and systematize these effective practices, not the other way around.

Limitations and Directions for Future Research

The PAL framework has been validated in more than ten primary schools and select secondary schools. To further solidify this framework, wider participation is needed. Future studies should focus on applicability in secondary schools or universities and comparative experiments with other teaching models. Furthermore, the requirements for teachers under PAL are stringent; teachers need a balanced and broad knowledge base as well as excellent problem-solving and hands-on skills. Consequently, comprehensive teacher training is a necessity for successful implementation.

Conclusion

The Project Approach in Learning (PAL) is a framework for STEM teaching and learning that provides a clear and holistic model based on various education theories. By integrating rigorous Project Planning, structured Lesson Arrangement, and cohesive Instructional Strategies, PAL addresses the practical challenges of modern technology education. It is our hope that PAL will serve as a common language for STEM educators, ensuring that "learning by doing" results in deep, transferable understanding and the capability to solve the real-world problems of tomorrow.

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Make It Maritime: A Simulation-Based Engineering Design Challenge Using Multimodal Technologies

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Abstract

This paper presents The Incredible Bulk, a multimodal, simulation-based engineering challenge that introduces Grades 4–12 to maritime careers and digital transformation. Students assume the roles of different maritime careers to assemble aircraft carrier bulkhead systems using: VR for spatial orientation and task preview; a 3D model as visual work instruction; paper blueprints for part identification and dimensioning; 3D-printed components for hands-on assembly; and an AR app for quality assurance/inspection. Grounded in constructionism and cognitive apprenticeship, the plan–build–inspect loop externalizes thinking and situates coached, authentic practice that advances engineering design, systems thinking, and technological literacy.

Keywords: cognitive apprenticeship, situated engineering practice, simulation-based learning, engineering design

Introduction

Technology and engineering education in recent years has shifted toward learning environments that reflect how engineering knowledge is developed, coordinated, and enacted in real-world settings. Rather than treating engineering as the application of decontextualized skills or isolated technical procedures, contemporary approaches emphasize authentic practice, situated cognition, and the orchestration of multiple representations, tools, and roles within complex systems (Dym et al., 2005; Johri & Olds, 2011; National Academy of Engineering, 2009). This shift aligns closely with the mission of the International Technology and Engineering Education Association (ITEEA) to advance engineering design, systems thinking, and technological literacy through meaningful engagement with real technological systems and practices (ITEEA, 2020).

Within this landscape, simulation-based and multimodal learning environments have emerged as particularly promising for engineering education. Research has shown that simulations, when designed to preserve the structure and cognitive demands of real work, can support conceptual understanding, design reasoning, and transfer beyond the instructional context (de Jong et al., 2013; Hmelo-Silver et al., 2015). However, much of the existing work in K–12 engineering education continues to focus on either purely digital simulations or isolated hands-on activities, with limited attention to how physical and digital representations can be systematically integrated to reflect authentic engineering workflows.

The maritime industrial base presents a compelling yet underutilized context for addressing this gap. Shipbuilding and ship repair require the coordination of spatial reasoning, blueprint interpretation, mathematical measurement, sequencing, and quality assurance within tightly coupled sociotechnical systems. Engineering work in these domains is rarely visible to novices, as it is distributed across representations, roles, and inspection processes rather than embodied in a single artifact or tool. As a result, students often lack both awareness of maritime careers and an understanding of how engineering knowledge is applied in large-scale industrial systems.

This paper presents The Incredible Bulk as a simulation-based engineering design challenge designed to make these invisible practices visible to K–12 learners. The activity introduces students in Grades 4–12 to maritime engineering through a role-based bulkhead assembly task that mirrors authentic shipfitting workflows. The purpose of this paper is threefold: (1) to position the challenge theoretically within cognitive apprenticeship and situated engineering practice; (2) to describe how multimodal simulation-based technologies function as mechanisms for engagement, sensemaking, and learning; and (3) to demonstrate how the use case supports both K–12 engineering education and a broader research agenda focused on workforce training for shipbuilding and ship repair.

Theoretical Foundations

Cognitive Apprenticeship in Engineering Education

Cognitive apprenticeship provides a foundational framework for understanding how complex professional practices can be taught and learned through guided participation in authentic activities (Collins, Brown, & Newman, 1989). Rather than isolating skills from context, cognitive apprenticeship emphasizes modeling expert practices, coaching learners during performance, scaffolding complex tasks, and supporting reflection and articulation. These processes are particularly relevant for engineering education, where expertise depends not only on procedural knowledge but on the ability to frame problems, interpret representations, and make trade-offs under constraint (Schön, 1983; Turns et al., 2014).

Within engineering education research, cognitive apprenticeship has been widely used to support design thinking and iterative problem solving, particularly in project-based and design-based learning environments (Crismond & Adams, 2012; Kolodner et al., 2003). Empirical studies demonstrate that apprenticeship-oriented approaches promote deeper conceptual understanding and greater transfer than instruction focused solely on procedures or end products (Hmelo-Silver et al., 2007; Prince & Felder, 2006).

In The Incredible Bulk, cognitive apprenticeship is operationalized through role-based participation and structured facilitation that mirrors maritime engineering workflows. Learners assume maritime-aligned roles such as planners, shipfitters, and inspectors, allowing them to engage with distinct yet interdependent aspects of the engineering process. Instructors model how blueprints are interpreted, how spatial constraints are anticipated, and how inspection criteria are applied, while gradually transferring responsibility to learners across iterations of the plan–build–inspect cycle. This approach positions learners as legitimate participants in engineering practice rather than passive recipients of instruction, aligning with situated learning theory and apprenticeship models used in professional engineering contexts.

Situated Engineering Practice and Multimodal Representation

Situated cognition theory argues that knowledge is inseparable from the contexts, tools, and social interactions in which it is developed and used (Lave & Wenger, 1991). Engineering work is inherently situated, relying on the coordination of multiple representational forms including drawings, models, physical artifacts, and digital interfaces. Research in engineering cognition has consistently shown that expert performance depends on fluency across these representations rather than mastery of any single one (Johri & Olds, 2011; Schön, 1983; Bucciarelli, 1994).

The design of The Incredible Bulk reflects this perspective by intentionally requiring learners to move between paper blueprints, 3D digital models, physical components, and augmented inspection overlays. These representations are complementary rather than redundant. Paper blueprints emphasize symbolic notation, dimensions, and tolerances, supporting disciplinary conventions central to engineering communication. The 3D digital model supports spatial reasoning and mental rotation, which are well-documented challenges for novice learners interpreting orthographic drawings (Uttal & Cohen, 2012). Physical assembly demands embodied engagement with alignment, sequencing, and constraint, while the AR inspection layer externalizes quality criteria and error detection.

This representational ecology supports what Johnson (2026a) characterizes as cognitive fidelity in simulation-based training, wherein learning environments preserve the cognitive structure of real work even when physical scale or complexity is reduced. Prior research demonstrates that coordinating multiple representations enhances conceptual change, supports transfer, and helps learners develop more robust mental models of complex systems (de Jong et al., 2013; Hmelo-Silver et al., 2015).

Simulation-Based Learning and Cognitive Systems

Within cognitive engineering contexts, simulation-based learning environments are increasingly understood as cognitive systems in which learners coordinate with tools, representations, and feedback mechanisms to accomplish tasks (Hollnagel & Woods, 2005; Hutchins, 1995). From this perspective, learning is not solely an internal cognitive process but emerges through interaction with the system as a whole. This framing is particularly relevant for industrial and maritime training, where performance depends on distributed cognition across people and technologies. Recent work in cognitive engineering and human–computer interaction has emphasized the role of adaptive interfaces, multimodal feedback, and externalized cognition in supporting learning and performance in complex environments (Johnson, 2025a; Johnson & Grant, 2026; Salas et al., 2009). Although The Incredible Bulk is designed for K–12 contexts, it draws on these same principles by treating VR, AR, and physical artifacts as coordinated system components rather than standalone instructional tools.

By framing the activity as a cognitive system, this work establishes a clear pathway for future research extensions. Specifically, the same design principles used in this K–12 use case are being leveraged to inform simulation-based training enhancements for shipbuilding and ship repair, including adaptive feedback mechanisms, inspection support tools, and representational scaffolds for novice workers. This continuity strengthens the contribution of the present paper and positions it as a foundation for subsequent journal publications.

Activity Design and Implementation

Overview of the Engineering Design Challenge

The Incredible Bulk engages students in a simulation-based engineering design challenge centered on assembling a scaled aircraft carrier bulkhead that serves as a structural and functional boundary within a ship. Rather than treating the bulkhead as a single static object, the challenge frames it as an integrated system that supports and constrains multiple shipboard functions. Student teams are tasked with assembling components that represent structural elements, penetrations, and interfaces for adjacent ship systems, requiring them to reason about how individual parts contribute to the integrity, safety, and operability of the larger vessel.

The activity is structured around an iterative plan–build–inspect workflow that reflects authentic maritime engineering practice and mirrors how engineering and trades teams collaborate in shipbuilding and ship repair. Students work collaboratively in small teams, with each learner contributing to planning, assembly, and inspection decisions. This structure reinforces the distributed nature of engineering work by requiring learners to coordinate roles, share information across representations, and negotiate design trade-offs as a group. Engineering decisions are therefore not isolated acts, but collective processes shaped by constraints, system interactions, and quality requirements.

The challenge begins with deliberate contextualization and background knowledge development, introducing learners to defining characteristics of maritime industrial environments and the critical role of bulkheads in ship structure, safety, and compartmentalization. Students learn that bulkheads are not merely walls but engineered systems that provide structural support, control the spread of fire and flooding, and create boundaries for shipboard systems such as piping, electrical routing, and mechanical equipment. This foundational understanding is essential for appreciating why precision, sequencing, and inspection are central to shipbuilding and ship repair.

Rather than presenting this background information abstractly, the activity situates learners within a simulated ship compartment using virtual reality (VR). The VR environment allows students to experience the spatial scale and constraints of a ship interior, including limited clearances, complex geometries, and the proximity of adjacent systems. By exploring the compartment virtually before assembly, learners gain an embodied sense of how bulkheads interact with surrounding structures and systems, supporting spatial reasoning and anticipatory planning. This immersion emphasizes load considerations, functional requirements, and access constraints that directly inform subsequent assembly decisions.

Following this immersive orientation, learners transition from virtual context to physical and digital assembly tasks, carrying forward an understanding of how their bulkhead assembly must accommodate multiple systems and future operations. This progression from contextual exploration to hands-on construction mirrors professional engineering workflows, in which designers and tradespeople move between conceptual models, digital representations, and physical workspaces. Throughout the challenge, students remain anchored in the idea that they are contributing to a larger engineered system, reinforcing systems thinking and highlighting the interdependence of engineering and skilled-trades roles.

By embedding system-level reasoning, role coordination, and representational transitions within the engineering design challenge, The Incredible Bulk enables students to experience maritime engineering as a dynamic, collaborative practice. The use of physical and digital simulation-based technologies not only supports learning of engineering concepts but also fosters engagement with the diverse careers involved in shipbuilding and ship repair. Students begin to understand how engineers, planners, machinists, welders, pipefitters, and inspectors collectively shape ship systems, transforming abstract career concepts into lived, participatory experiences within the design challenge, see Figure 1 below.

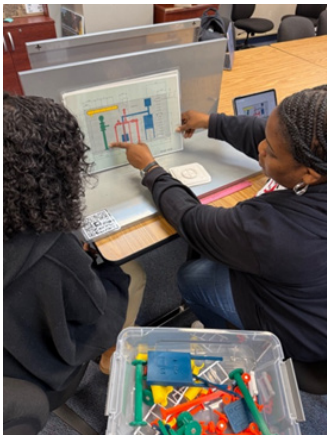

Figure 1.
Educators during a professional development session engaging with The Incredible Bulk engineering design challenge blueprints planning their components prior to assembly and measurement with 3D-printed, physical learning artifacts.

Multimodal Engagement Through Physical and Digital Artifacts

A central design principle of The Incredible Bulk is the deliberate integration of physical learning artifacts with digital representations to support spatial reasoning, blueprint literacy, mathematical reasoning, and situated exposure to maritime careers. Rather than treating careers as peripheral content delivered through videos or guest speakers, the engineering design challenge embeds career roles directly into the activity structure, allowing students to experience how different professionals contribute to shipbuilding and ship repair through coordinated action.

Learners engage with paper-based blueprints to identify components, interpret dimensions, and calculate measurements required for assembly, positioning them in practices closely aligned with those of planners, engineers, and machinists. For many learners, particularly in upper elementary and middle school, blueprint interpretation represents a significant cognitive challenge when encountered in isolation. Within the challenge, however, blueprint work is framed as purposeful decision-making that mirrors how planners and engineers communicate intent and constraints to downstream trades.

The inclusion of a corresponding 3D digital model allows learners to map symbolic information from the blueprint onto a spatial representation, supporting mental rotation and reducing extraneous cognitive load (Sweller, 1988; Uttal & Cohen, 2012). This coordination between representations helps learners develop more accurate mental models of the structure and supports transfer to novel configurations. From a career perspective, the 3D model functions as a proxy for the digital work instructions and visualization tools increasingly used by

engineers, planners, and machinists in modern shipyards, making explicit how digital technologies mediate real-world engineering work, see Figure 2 below.

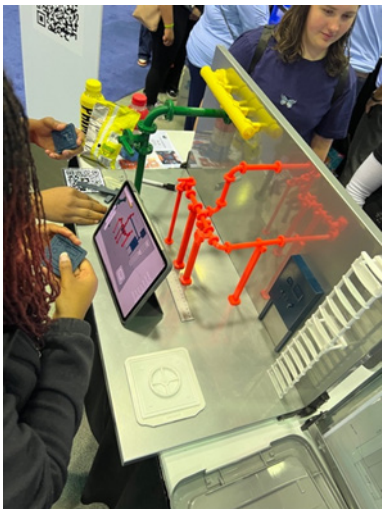

Figure 2.
Middle school students engaging with the 3D model, measurement tool, and 3D-printed learning artifacts to complete their next component assembly in The Incredible Bulk engineering design challenge.

The utilization of 3D-printed components extends this representational work into embodied action. As learners assemble components, they must attend to orientation, alignment, sequencing, and tolerances, reinforcing the relationship between abstract plans and concrete outcomes. These hands-on assembly practices align closely with the work of pipefitters, welders, and inside and outside machinists, whose expertise depends on translating drawings and specifications into precise physical configurations. Mathematical concepts such as measurement, proportional reasoning, and precision are embedded naturally within the task, aligning with research demonstrating that contextualized mathematics supports deeper understanding in engineering education (Nathan et al., 2013). Importantly, this component of the challenge is intentionally scaffolded across grade levels, ranging from place-value and whole-number measurement in early elementary grades to decimal precision, tolerances, and unit conversion in middle and high school, mirroring the developmental progression of technical skill within the trades.

The AR-based quality assurance component further extends learning by introducing inspection as an explicit engineering practice and by foregrounding the role of the quality assurance inspector within shipbuilding and ship repair. Rather than treating correctness as binary, the inspection phase emphasizes criteria-based evaluation, error detection, and iterative improvement. By overlaying inspection cues onto the physical assembly, the AR tool externalizes expert judgment and supports reflective discussion about design quality, rework, and acceptance standards, see Figure 3 below. This mirrors industrial inspection practices and highlights how quality assurance functions as a critical, decision-oriented role that interfaces with engineers, planners, and tradespeople. The approach aligns with Johnson's (2026b) work on making invisible cognitive demands visible through technology-enhanced simulation.

Figure 3.
Augmented reality (AR) inspection of one of the pipefitting component assemblies in The Incredible Bulk engineering design challenge. The AR tool provides real-time feedback for teams in how to iterate their assembly components, in addition to conversations on how the maritime industry is using digital technologies for training and operations.

These multimodal engagements position career learning as an outcome of participation in practice, consistent with cognitive apprenticeship theory. Students do not merely learn about shipbuilding and ship-repair careers; they learn through them by adopting role-based perspectives, coordinating with teammates performing complementary functions, and experiencing how engineering, trades, planning, machining, and inspection are interdependent within a complex system. This form of firsthand engagement stands in contrast to more traditional career awareness approaches, such as videos or panel discussions, by allowing learners to enact professional roles, negotiate constraints, and experience the cognitive and collaborative demands of maritime work as they complete the engineering design challenge.

Facilitation and Apprenticeship-Oriented Instruction

Instructor facilitation plays a critical role in ensuring that the activity functions as a cognitive apprenticeship rather than an unguided construction task. Facilitators model expert strategies for interpreting blueprints, anticipating spatial challenges, and conducting inspections, while prompting learners to articulate their reasoning and reflect on errors. Scaffolding is gradually reduced as learners demonstrate increased competence, supporting autonomy while maintaining task fidelity.

Importantly, facilitation emphasizes dialogue, justification, and sensemaking rather than procedural compliance. This aligns with research demonstrating that reflective discussion during engineering design activities enhances transfer, metacognitive awareness, and conceptual understanding (Crismond & Adams, 2012; Kolodner et al., 2003). The plan–build–inspect cycle provides natural opportunities for feedback and revision, reinforcing engineering as an iterative, knowledge-building process rather than a linear task.

Standards Alignment and Educational Relevance

The Incredible Bulk aligns strongly with ITEEA's *Standards for Technological and Engineering Literacy (STEL)* through its emphasis on engineering design as an iterative, systems-oriented process situated within real technological contexts (ITEEA, 2020). The engineering design challenge explicitly engages learners in defining problems, interpreting constraints, developing and using representations, testing solutions, and refining designs through inspection and revision. These practices are not presented as abstract steps but are enacted through coordinated activity with physical and digital artifacts, reinforcing *STEL*'s emphasis on technological systems, design thinking, and the societal relevance of engineering work.

The activity also aligns with the Virginia Department of Education's Standards of Learning (SOLs), Computer and Technical Education competencies, and *Next Generation Science Standards (NGSS)* engineering design practices, particularly those related to developing and using models, planning and carrying out investigations, analyzing data through inspection and measurement, and optimizing solutions under constraint (NGSS Lead States, 2013). Learners use multiple models, such as paper blueprints, 3D digital representations, and physical assemblies to reason about structure and function, supporting *NGSS* goals related to modeling, evidence-based reasoning, and iterative improvement. The plan–build–inspect cycle provides repeated opportunities for learners to test assumptions, identify errors, and revise designs, reinforcing engineering as a knowledge-building process rather than a one-time task.

Beyond formal standards alignment, The Incredible Bulk addresses a critical educational need to broaden awareness of maritime careers and pathways in ways that are developmentally appropriate and cognitively meaningful, while aligning to CTE competencies for educators. By situating learning within authentic shipbuilding and ship-repair practices, the challenge enables students to see how familiar technologies such as VR, AR, and 3D printing are embedded within professional engineering and trades workflows. This approach reframes digital tools not as ends in themselves, but as mediators of real-world engineering work, supporting technological literacy and informed career exploration.

Importantly, the activity supports vertical alignment and cross curricular engagement across grade levels by allowing core practices, such as blueprint interpretation, spatial reasoning, measurement, and inspection, to be scaffolded in complexity. This flexibility enables alignment with elementary, middle, and high school learning goals while maintaining fidelity to authentic engineering practice. As such, The Incredible Bulk serves as both a standards-aligned instructional resource and a model for how engineering design challenges can integrate career awareness without sacrificing conceptual rigor.

Evaluation and Research Use

Evaluation of The Incredible Bulk is designed to support both classroom instruction and research-oriented inquiry without imposing burdensome data collection requirements. Classroom-appropriate measures focus on learner engagement, representational understanding, and participation in engineering practices. Observational protocols capture how learners interact with teammates, navigate between representations, and respond to feedback during the plan–build–inspect cycle. Student artifacts, including annotated blueprints, assembled components, and inspection outcomes, provide evidence of representational fluency and design reasoning. Rubric-based assessments support formative and summative evaluation of blueprint interpretation, measurement accuracy, and quality assurance decision-making.

These approaches align with prior research on assessing learning in simulation-based and design-centered environments, which emphasizes the value of performance-based measures and artifact analysis over decontextualized testing (de Jong et al., 2013; Hmelo-Silver et al., 2015). By focusing on observable practices and design outcomes, the evaluation framework supports instructional improvement while generating data that can inform broader research questions.

Beyond classroom use, data and insights from The Incredible Bulk contribute to a larger research agenda focused on simulation-based training for shipbuilding and ship repair. Patterns observed in learner errors, representational breakdowns, and inspection decisions provide early indicators of where novices struggle when coordinating physical and digital information. These findings inform ongoing work on cognitive systems, adaptive interfaces, and expertise development in industrial training contexts (Johnson, 2025b; Johnson & Grant, 2026). In this way, the K–12 use case functions as an exploratory testbed for concepts that scale into workforce training research, supporting continuity across educational and professional domains.

Discussion and Implications

This use case demonstrates how cognitive apprenticeship and situated engineering practice can be operationalized in K–12 settings through thoughtfully designed multimodal simulation-based technologies. By integrating physical artifacts with digital representations, The Incredible Bulk supports deep engagement with engineering concepts while maintaining accessibility across grade levels, resource contexts, and learner backgrounds. The activity illustrates how engineering design challenges can preserve the cognitive structure of professional practice without requiring full-scale industrial environments.

For technology and engineering educators, the challenge offers a concrete example of how emerging technologies such as VR and AR can function as cognitive supports rather than standalone instructional novelties. The integration of representations encourages learners to reason across symbolic, spatial, and physical domains, reinforcing transferable engineering habits of mind. The role-based structure further supports collaboration and communication, aligning with professional engineering practice and teamwork expectations.

For researchers and workforce developers, The Incredible Bulk highlights the potential of K–12 engineering education to serve as an entry point into longer-term expertise development. Early exposure to authentic practices, representational coordination, and inspection-oriented thinking may support smoother transitions into technical education, apprenticeships, and industry training. By framing the activity as part of a broader cognitive systems perspective, this work contributes to ongoing discussions about how simulation-based learning can bridge educational levels and support workforce readiness in complex industrial domains.

Conclusion

The Incredible Bulk offers a theoretically grounded, standards-aligned example of how simulation-based engineering challenges can support cognitive apprenticeship and situated learning in K–12 education. Through the deliberate integration of physical artifacts, digital representations, and role-based participation, the activity makes maritime engineering practices visible, accessible, and meaningful to learners. In doing so, it advances technological literacy, engineering design competence, and career awareness while contributing to a broader research agenda on simulation-based training for complex industrial systems. As a use case, The Incredible Bulk demonstrates how K–12 engineering education can be designed not only to meet standards but also to inform future research and workforce development efforts. The approach provides a foundation for expanded studies examining learning outcomes, representational fluency, and transfer across educational and professional contexts, positioning this work for continued impact beyond the classroom.

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Strategies for Using AI to Promote UDL in STEM Courses

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Abstract

As educators increasingly use Artificial Intelligence (AI) for personalized support and adopt Universal Design for Learning (UDL) to foster inclusive engagement in STEM, there is a practical need to understand how these two concepts intersect. This paper addresses this need by investigating how strategies for leveraging AI to enhance STEM learning environments through the UDL framework have been attempted and presents findings from the present study. We explored how AI-driven tools and techniques can be used to promote flexibility, accessibility, and engagement, embodying UDL fundamentals in the technology and engineering education and STEM education literature. After implementing AI strategies in our own courses, we collected end-of-course survey of responses from 80 undergraduate students from introductory non-major courses to upper-level engineering technology courses. The survey incorporated items from the Metacognitive Awareness Inventory and Novak's UDL Self-Reflection to capture quantitative and qualitative data.

Analysis focuses on student and instructor perceptions of the learning environment, supported by specific examples of how AI-leveraged strategies were deployed. Key findings related to metacognitive awareness and the perceived effectiveness of specific AI-driven UDL strategies will be presented. This research provides practical, data-driven implications for educators and researchers seeking to integrate AI to create more inclusive and effective STEM classrooms, offering a model for broader implementation and future study.

Keywords: Artificial Intelligence (AI), Universal Design for Learning (UDL), STEM Education, Metacognitive Awareness

Introduction

A significant challenge in postsecondary education is the transition from instructor-led learning to autonomous self-regulation. The affective network, targeted by the Universal Design for Learning (UDL) principle of Multiple Means of Engagement, plays a pivotal role in this transition. By providing checkpoints for self-assessment and reflection, UDL shifts the evaluative burden from the instructor to the learner, which enhances student self-efficacy (Batmaz Derer & Cosken, 2021). When students monitor their own persistence and frustration levels, they are performing "Metacognitive Regulation," which Schraw and Dennison (1994) identified as a key predictor of academic success. Another key principle of UDL, Multiple Means of Representation, facilitates the development of knowledge. By presenting information in varied modalities, UDL-aligned curricula allow students to identify which sensory and cognitive pathways are most efficient for their unique learning profiles. This self-discovery is the essence of metacognitive awareness. As students realize they comprehend complex data more effectively through visual diagrams than through dense text, they gain the skills and confidence required to seek out similar resources in future, non-scaffolded environments.

The transition to autonomous self-regulation is particularly critical in STEM disciplines, where traditional "gateway" courses often feature high-pressure environments and rigid pedagogical structures that can inadvertently alienate students. Seminal research indicates that the departure of underrepresented students from STEM majors often stems more from a reduced sense of social belonging than from a lack of academic preparedness (Seymour & Hewitt, 1997). Recent studies find that these issues persist: a strong sense of belonging is a key predictor of academic success and retention; students who feel they fit within their disciplinary community are more likely to remain engaged and persist when faced with rigorous coursework (Hammarlund et al., 2025; Hansen, 2023). By implementing UDL principles, educators can create inclusive STEM environments that

actively recruit interest and sustain effort by affirming students' identities and individual assets. Such environments mitigate "stereotype threat" and reduce feelings of isolation, which are significant factors in student attrition (Killpack & Melón, 2016). Ultimately, fostering a sense of belonging through inclusive design not only improves individual student performance but also addresses broader systemic gaps in STEM retention (Hammarlund et al., 2025; Hansen, 2023).

The Universal Design for Learning (UDL) framework is built on three core principles: providing multiple means of engagement to motivate learners (the "why"), representation to present information in diverse ways (the "what"), and action and expression to allow students to demonstrate their knowledge differently (the "how"). The goal of these principles is to remove barriers to learning and develop "expert learners" who are purposeful, resourceful, and strategic. (CAST, 2018). In this paper, we explored the relationship between UDL and metacognitive awareness as self-reported by 80 undergraduate students in three levels of engineering technology courses. In an effort to establish a classroom environment that promoted UDL goals, AI was used to address perceived opportunity areas identified by two instructors who taught these courses.

Literature Review

UDL in the STEM Classroom

UDL as a pedagogy strategy in STEM classrooms has largely been utilized as an accommodation, particularly for students with disabilities. Multiple studies have focused on using UDL to support inclusivity for students with disabilities, with many finding that the results of various interventions were also beneficial for non-disabled students (Amos et al., 2021; Izzo, 2012; Izzo & Bauer, 2015; Moon et al., 2012). Schreffler et al. (2019) synthesized the empirical literature on Universal Design for Learning (UDL) in postsecondary STEM education, providing a model of its impact on instruction, including increased use of inclusive teaching methods and student self-advocacy. They concluded that UDL in STEM can be effectively implemented in postsecondary STEM education to improve student retention and persistence (particularly among students with disabilities), as it focuses on changing the learning environment rather than just providing accommodations. Basham and Marino (2013) concluded that the UDL framework can increase the usability of STEM curricular materials and improve educational experiences for a wide range of students with diverse learning needs. For example, by applying UDL in Engineering Design, they suggested that teachers can apply the engineering design process, which is central to STEM education, in multiple contexts for students with disabilities by creating engaging learning environments and encouraging problem-solving in their communities.

AI to Support UDL in the STEM Classroom

Recent research indicates a growing consensus on integrating Artificial Intelligence (AI) and UDL frameworks to create more inclusive academic environments. Researchers have identified how AI drives the core UDL pillars of flexibility (representation), accessibility (accommodation), and engagement (motivation). AI and UDL promote equity by transitioning STEM education from a "one-size-fits-all" model to a learner-centered approach that accommodates learner variability (Leon et al., 2025). The intentional integration of AI and UDL offers the potential to transform instruction, narrowing achievement gaps and personalizing instruction at scale for a diverse group of STEM learners (Kohnke et al., 2025).

AI-driven tools facilitate UDL's Multiple Means of Representation principle by providing multimodal content delivery (Kohnke et al., 2025). In terms of promoting flexibility or representation, Kalaigian et al. (2024) provide evidence from traditional STEM classrooms where generative AI has been utilized to create avenues toward multiple means of representation. Examples include students employing AI to transform collected scientific data into simplified summaries, diagrams, or other visual figures, personalized to individual cognitive abilities or preferences. As noted by Saborío-Taylor & Rojas-Ramírez (2024), this method allows for a spectrum of defining STEM by creating individualized entry points into STEM content. These systems provide students with opportunities to adapt materials to their specific cognitive abilities.

Equitable STEM environments require students to develop higher-order thinking skills, such as critical thinking and inquiry-based learning (Leon et al., 2025). AI tools have been shown to act as "cognitive partners" that scaffold metacognitive processes such as planning, monitoring, and evaluating, which are necessary for iterative problem-solving in STEM (Tsakeni et al., 2025). Systems like generative chatbots encourage students to formulate questions, evaluate AI-generated outputs, and reflect on their reasoning processes. Regarding accessibility or accommodation, Hyatt and Owenz (2024) found, through case analysis, that AI can serve as a critical intervention for students with significant disabilities. By offering students an autonomous way to simplify content and receive phonics support, the system helped break down traditional barriers to literacy. These examples suggest a shift toward a conceptual model in which accessibility is built into the classroom structure rather than added later as an additional post-evaluation accommodation for each student.

The element of engagement or motivation can be addressed through frameworks that prioritize student agency and autonomy. Kloub (2025) found that AI-driven platforms can empower students by providing immediate, non-judgmental feedback, potentially fostering a growth-oriented mindset. Mazza & Allen (2025) also suggested that AI can enhance pedagogy by creating an engagement spectrum. Furthermore, AI and UDL can dismantle systemic barriers that discourage minority and marginalized students from pursuing STEM careers (Kohnke et al., 2025) by enhancing cultural contextualization and challenging implicit biases (Salas-Pilco et al., 2022). This supports a broader goal of having students interact with material through AI interfaces that is ethically designed and culturally responsive. Taken together, these studies indicate that while some specific details about AI implementation in the classroom have shown potential, some remain up for debate.

UDL and Metacognition

UDL serves as an essential instructional architecture for fostering metacognitive development (Galkienė & Monkevičienė, 2021; García-Campos et al., 2020). While traditional instructional models often treat metacognition as an implicit by-product of learning, the UDL framework explicitly scaffolds the cognitive processes that enable students to become expert learners. By analyzing the intersection of these two constructs, it becomes evident that UDL is an ideal vehicle for increasing both metacognitive knowledge and regulation. The brain's strategic network, which governs the "how" of learning, is directly addressed by the UDL principle of Multiple Means of Action and Expression. The research by Katz (2015) and Nelson (2021) suggests that providing students with flexible options for demonstrating knowledge is not merely about accessibility but about exercising executive functions. When students are required to choose between diverse tools for composition or problem-solving, they are forced to engage in planning and strategy selection. These actions directly correspond to the "Procedural Knowledge" and "Planning" subscales of the MAI. This explicit practice in decision-making transforms the classroom into a laboratory for strategic thinking.

Metacognitive awareness is a malleable construct that correlates significantly with academic achievement and clinical reasoning across diverse educational contexts (Young & Fry, 2008; Xuan Nguyen et al., 2023). Investigations of metacognition in STEM classrooms has shown that a student's "inner coach" is often more important for success than their IQ. Research suggests that technical skill is not just about being "smart"; it is about how well a student can monitor their own work when something goes wrong. For example, when a 3D-printed bridge prototype fails a stress test, students who score high on the MAI's debugging and monitoring scales do not give up. Instead, they employ specific strategies to identify the weak point in the structure and rectify it (Veenman & Verheij, 2003). In practical terms, metacognition has been demonstrated to be a reliable predictor of how effectively students manage complex technologies, such as Computer-Aided Design (CAD) software. Students with strong information management skills are better at organizing their digital files and navigating the numerous tools in programs such as SolidWorks or AutoCAD (Young & Fry, 2008). Furthermore, research shows that how we teach matters. When students are given a "recipe" lab where they just follow steps to build a simple circuit, their metacognitive growth is low. However, when they are given a messy, open-ended challenge—such as "design a water filtration system using only these five items"—their planning and evaluation scores on the MAI increase significantly. These high-challenge environments compel students to consider their choices, which fosters the "expert learner" habits necessary for real-world engineering challenges.

Methodology

Research Design

This non-experimental, mixed-methods study employed a cross-sectional design to gather both quantitative scores and qualitative perceptions of undergraduate students enrolled in 16-week engineering technology courses at a mid-sized, suburban R2 university. A total of 125 students were surveyed toward the end of the term, with 80 fully completed responses received (64%). Surveys with incomplete responses were excluded from analysis. Of the 80 respondents, 47 (58.75%) were from students in a "level 1" course (introductory STEM), 23 (28.75%) were from students in a "level 2" course (technical focus), and 10 (12.5%) were from students in a "level 3" course (capstone). All participants were students within the same degree program to ensure consistency in the academic culture and expectations across the "levels."

The goal of this study was to begin a preliminary investigation into how AI can be leveraged to develop, implement, and assess UDL in STEM curriculum environments. Three AI strategies were implemented. At all levels, the primary AI strategy was the use of an AI chatbot-style tool constrained to materials provided by the course instructor (not open to the public internet, etc.). This included specific course content, such as textbooks and other reading materials, videos, and targeted websites. Students were able to interact with this material in a variety of ways. They could chat with the platform to ask questions, create visual and audio summaries of the material, and add their own materials and resources from the class (such as lab sheets or graded work to gain feedback, etc.). The second AI strategy was to generate topic summary sheets and examples (by the instructor and used in course documents) to simplify complex, technical procedures, break them down into digestible steps, and reduce unnecessary information. The third implementation, which was used sparingly, was AI as a coding partner, document reviewer, creative ideas generator, and planner, intended as a tool for debugging, problem-solving, and thinking through problems. These three strategies were chosen to map directly to UDL principles: the constrained chatbot for Representation, summary sheets for Engagement/scaffolding, and the coding partner for Action and Expression.

Instrumentation

The online questionnaire consisted of two distinct, pre-validated instruments used in tandem to capture different facets of the student experience. The Metacognitive Awareness Inventory (MAI) is a 52-item self-report instrument based on the work of Schraw and Dennison (1994) that measures metacognitive awareness in adults and adolescents. It was developed to provide a reliable, easily administered alternative to more time-consuming methods such as verbal interviews or online experimental testing. The MAI used in this study consisted of 52 True/False questions organized into two main sections: Knowledge About Cognition and Regulation of Cognition. Within Knowledge About Cognition, sub-sections of Declarative, Procedural, and Conditional Knowledge can be summed. Similarly, the sub-sections of Regulations of Cognition consist of Planning, Information Management Strategies, Comprehension Monitoring, Debugging Strategies, and Evaluation. For each section, the practitioner assigns a total score and compares it to the total possible score to identify opportunities for improvement.

The survey also contained 14 items from the UDL Student Feedback Survey, developed by Novak (2022). Intended as a feedback tool for practitioners, this instrument assesses learners' perceptions of inclusive design principles in their instructional environment. This specific instrument was selected for the current study due to its high availability to practitioners and its inherent simplicity in administration and analysis. The survey is organized into subscales that correspond to the three primary pillars of the UDL framework as defined by CAST (2018). The first subscale focuses on Multiple Means of Engagement, evaluating learner interest, the perceived relevance of the curriculum, and the degree of self-regulation that the instructor fosters. The second subscale, Multiple Means of Representation, measures the accessibility of information and the variety of formats, such as digital, visual, or auditory media, provided to support diverse decoding strengths. Finally, the Multiple Means of Action and Expression subscale assesses the availability of diverse assessment options and the degree to which learners are supported in developing executive functions and strategic planning. According to Novak

(2022), this structural alignment ensures that the instrument captures a comprehensive view of the instructional environment from the learner's perspective. Prior research (e.g., Novak & Thibodeau, 2016) has revealed a frequent discrepancy between instructors' self-perceptions and student feedback, underscoring the utility of this survey for identifying specific areas where instructional flexibility remains limited despite practitioners' intent.

Results

Attention was given to the MAI results where groups had the lowest average score. Students in level 1 reported the lowest level of Declarative Knowledge (6.47), Information Management Strategies (7.96), and Debugging Strategies (4.64). Students in level 2 scored the lowest overall MAI score (41.52), Planning (4.52), Comprehension Monitoring (5.26), Evaluation (4.17), and in the subtotal for Regulation of Cognition (27.04). Students in level 3 scored lowest in Procedural Knowledge (3.30), Conditional Knowledge (4.30), and the Knowledge About Cognition subtotal (14.20). Table 1 shows the mean MAI results by level. The total possible points for each category are shown.

Table 1.
Mean Results of the Metacognitive Awareness Inventory (MAI) by Level

Level	1	2	3	4
Declarative Knowledge (8)	6.47	6.65	6.60	6.54
Procedural Knowledge (4)	3.49	3.43	3.30	3.45
Conditional Knowledge (5)	4.32	4.39	4.30	4.34
Knowledge About Cognition Total (17)	14.28	14.48	14.20	14.33
Planning (7)	5.40	4.52	5.50	5.16
Information Management Strategies (10)	7.96	8.35	8.60	8.15
Comprehension Monitoring (7)	5.98	5.26	5.80	5.75
Debugging Strategies (5)	4.64	4.74	4.90	4.70
Evaluation (6)	4.36	4.17	4.60	4.34
Regulation of Cognition Total (35)	28.34	27.04	29.40	28.10
MAI Overall Score (52 items)	**42.62**	**41.52**	**43.60**	**42.43**

The UDL survey provided context and comparison for the MAI results. According to Novak (2022), UDL Student Feedback results below a score of 4 (on a 5-point Likert scale) should be considered by educators as indicators for improvement opportunities. Among the three groups of students, four questions had average responses below this threshold. One question, "I love being a part of this classroom because the community feels like family," yielded average responses below 4 for each group. Additionally, in the 100-level group, "My teacher really gets me" (3.38) and "I am encouraged to set goals for my learning interests" (3.91) were below the 4-point threshold. Table 2 shows the mean results of the UDL Student Feedback survey by level.

Table 2.
Mean Results of the UDL Student Feedback by Level

Level	1	2	3	4
I understand why everything I am learning in this class is important.	4.06	4.13	4.30	4.11
I feel safe and accepted in our classroom for who I am.	4.57	4.65	4.90	4.64
My teacher really gets me and knows my interests, my life outside of school, and how I learn best.	3.38	3.43	4.30	3.51
In this class, I am provided with choices for how I will learn new knowledge and skills.	4.13	4.30	4.30	4.20
When I am having a difficult time in class, I know what strategies and resources to use to get back on track.	4.17	4.22	3.90	4.15
I love being a part of this classroom because the community feels like a family.	3.53	3.96	3.80	3.69
The class is designed so I always have the support I need in order to challenge myself.	4.00	4.48	4.30	4.18
My teacher is great at helping me to believe in myself as a learner who can meet high expectations.	4.02	4.39	4.60	4.20
I receive helpful feedback and tips from my teacher to help me reach my goals.	4.21	4.17	4.70	4.26
I am provided with opportunities to reflect on my learning and think about what I need to work on to be a better learner.	4.15	4.22	4.50	4.21
I am provided with choices in how I show what I have learned.	4.13	4.00	4.40	4.13
I am allowed to use tools and technology to help me learn and show what I have learned.	4.43	4.57	4.60	4.49
I am encouraged to set goals for my learning using my own interests	3.91	4.00	4.50	4.01
I am learning how to keep organized and create action plans for completing my work.	4.11	4.09	4.10	4.10

Discussion

The findings of this study indicate a growing consensus that AI can serve as a critical “cognitive partner” in enabling the three pillars of UDL in STEM environments. The data from the Metacognitive Awareness Inventory (MAI) revealed opportunities for improvement across all three levels studied. It also showed a potentially significant moment at “Level 2,” where students exhibited the lowest overall Regulation of Cognition. The observed dip in the Regulation of Cognition (27.04) for Level 2 students suggests a “metacognitive plateau” that often occurs when students transition from foundational concepts to high-rigor technical application. While Level 1 students may rely on general study habits, Level 2 courses are typically characterized by complex CAD software or circuit analysis that demand specialized Information Management and Debugging Strategies. The data implies that as technical complexity increases, students’ internal “inner coach” may become overwhelmed. This identifies a critical “scaffolding gap” where AI intervention is most necessary. By utilizing constrained chatbots to provide immediate, non-judgmental feedback, instructors can prevent the cognitive overload that leads to frustration and attrition in middle-tier STEM courses. While AI tools were highly rated for providing Multiple Means of Representation, the UDL survey results for “My teacher really gets me” (3.51) and classroom “family” community (3.69) highlight a significant boundary in AI-driven instruction, suggesting that while AI can act as a “cognitive partner” for technical tasks, it cannot yet simulate the “affective network” required for a true sense of

belonging. This finding underscores the necessity of human-AI synergy: AI should be used to offload the repetitive "scaffolding" tasks (such as summarizing procedures or debugging code), thereby freeing the instructor to focus on high-touch relational work. For underrepresented students, the departure from STEM is often rooted in isolation rather than a lack of ability. Therefore, the instructor's role as a "human intermediary" who validates student identity and fosters social belonging remains the indispensable core of an inclusive STEM environment.

Taken together, the findings from this study suggest that AI integration is not merely an afterthought or an additive accommodation but can be part of a functional shift toward a learner-centered infrastructure that accommodates individual learner needs on a broader scale. By embedding these modifications into the digital framework, educators can help dismantle the "one-size-fits-all" model and support the growth of self-efficacy necessary for students to thrive in rigorous STEM disciplines.

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Dr. Jeritt Williams is an Assistant Professor of Engineering Technology at Illinois State University, where he specializes in advancing robotics and automation education. Recognized for his leadership and impact on the industry, he recently earned the distinction of 2025 A3 Educator of the Year. At Illinois State, he directs the Caterpillar Integrated Manufacturing Lab, a premier facility that transforms technical education through high-impact, hands-on instruction in systems integration, including industrial robotics, PLCs, and digital twin technologies. Drawing on two decades of experience across industry and education, Williams is dedicated to bridging the gap between scholarship and practice. Williams's body of academic work focuses on STEM-related professional identity formation. Dr. Williams currently serves as a co-Principal Investigator on "SUPERCHARGE" (NSF Award #2148429), which aims to increase support for traditionally underserved STEM talent pathways involving robotics and renewable energy. He is also co-leading the development and pilot testing of an "AI+Robotics" micro-credential for STEM educators, ensuring that students are rising to the challenge of meeting the rapidly evolving demands of the next generation workforce.

Our Inconvenient Truth

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Abstract

In An Inconvenient Truth *(2006), Al Gore warned of a global crisis rooted in human inaction and lack of foresight. Technology and Engineering Education (TEE) faces its own inconvenient truth. Since 1990, the field has seen an 80 percent decline in undergraduate programs and a 91 percent decline in undergraduate students—a decline so severe that it threatens the discipline's existence. Yet renewal is possible.*

TEE's mission remains essential: To ensure a foundational level of technological and engineering literacy for all learners while serving as a feeder and pathway to community college and university technician and engineering education programs.

By clarifying this mission and embracing the integration of computer science—linking computational thinking with engineering design pedagogy and project-based learning—TEE can empower learners not only to work with technology but to find meaning and creativity through it. In doing so, the field can regain vitality, becoming an integrating framework that connects technological competence with human fulfillment in a world where technology shapes nearly every dimension of experience.

Keywords: Computer Science Integration; Teacher Pipeline Development; Teacher Preparation and Recruitment; Technology and Engineering Education

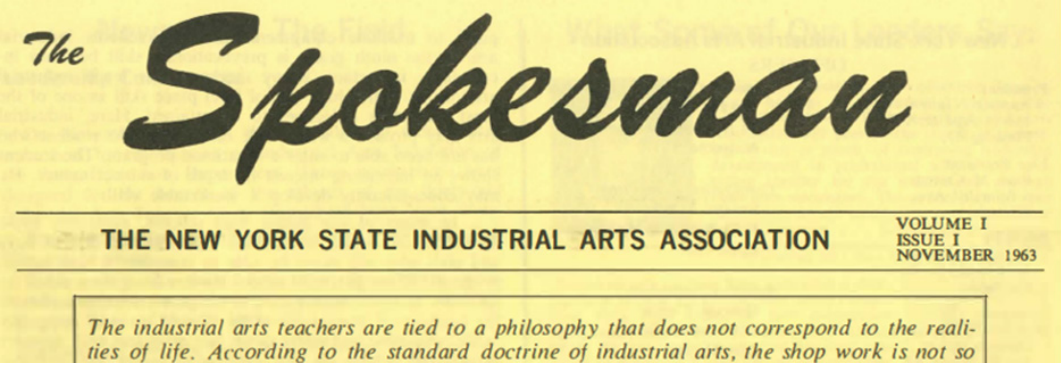
Introduction

In *An Inconvenient Truth* (Gore, 2006), Al Gore highlighted the urgency of global climate change, attributing it primarily to human activities—especially the burning of fossil fuels, which increases atmospheric greenhouse gas concentrations. The book helped popularize terms like "global warming" and significantly raised public awareness of climate change as a moral and global issue. It played a major role in bringing climate science into mainstream conversation.

This paper makes no such claims. Its goal is more modest, but the author hopes still meaningful: to encourage professional dialogue about the role and intent of the technology and engineering education (TEE) discipline in light of the most dramatic technological changes in history due to the rapid deployment of automation, artificial intelligence, advanced systems, and data analytics.

Interest in writing this paper was sparked by an article in Volume I, Issue I of *The Spokesman*, the inaugural newsletter of the New York State Industrial Arts Association, dated November 1963 (see Figure 1). James Bryant Conant was a highly influential American chemist, educator, and public servant. He was president of Harvard University from 1933 to 1953 and was a strong proponent of comprehensive high schools that serve all students, college-bound and vocational, under one roof. Figure 1 shows a snapshot of the newsletter. The complete quote that follows comes from his book *Slums and Suburbs* (Conant, 1961):

Figure 1.
The Spokesman *article, November 1963*


The Spokesman

THE NEW YORK STATE INDUSTRIAL ARTS ASSOCIATION

VOLUME I
ISSUE I
NOVEMBER 1963

The industrial arts teachers are tied to a philosophy that does not correspond to the realities of life. According to the standard doctrine of industrial arts, the shop work is not so

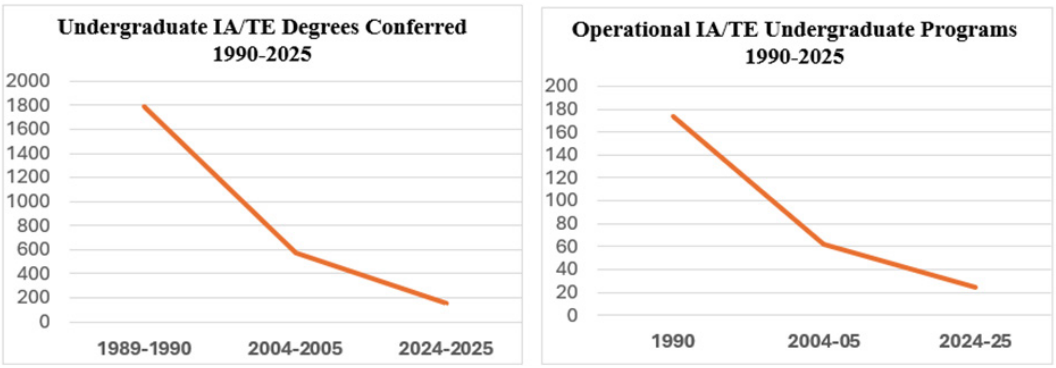
Conant wrote:

> The industrial arts teachers are tied to a philosophy that does not correspond to the realities of life. There is considerable literature written by the proponents of the industrial arts which sets forth the standard doctrine. This doctrine is that the objective of the practical work is not so much to acquaint a boy with how to use tools and handle materials as to give him a practical acquaintance with the industrial world. Industrial arts are seen as general education. No real skill is developed, but a bowing acquaintance with the manipulation of the physical objects is provided. The theory is that such exposure makes the boy a more knowledgeable citizen in our industrialized and urbanized society. I have never seen any evidence to support this theory. In my view, a knowledge of science and mathematics, in addition to comprehension of the nature of our society provided in social science courses—in short, the required general education program—is more relevant to this purpose than work in the industrial arts (Conant, 1961, pp. 106–107).

What is Our Inconvenient Truth?

Over the past two decades, the number of programs in Industrial Arts/Technology Education/Technology and Engineering Education nationwide has declined by 60% (from 62 to 25 programs), and the yearly number of undergraduate degrees conferred has declined by 73% (from 577 to 159 undergraduate degrees) (Hacker, 2025). Since 1990, there has been an 86% decline in undergraduate degree-granting programs (from 174 to 25 programs) and a 91% decline in undergraduate degrees granted (from 1790 to 159 undergraduate degrees), shown in Figure 2. For a current listing of undergraduate programs and enrollments, see https://www.hofstra.edu/sites/default/files/styles/large/public/2025-10/listing-of-technology-education-undergraduate-degree-programs.pdf.

Figure 2.
Decline in Undergraduate AI/TEE Degrees Conferred and in Operational Undergraduate TEE Programs, 1990-2025.



We often hear anecdotally that university TEE faculty are contacted by LEAs seeking teachers, and that the universities are unable to meet the demand. This leads to program closures, and in the case of New York State, the substitution of a generic Career and Technical Education (CTE) requirement (NYSED, 2019) for the one-unit middle school Technology Education requirement that had been in place since 1984 (WESTLAW, 2021).

Literature Review

Between 2011 and 2022, undergraduate teacher preparation programs nationwide remained generally stable while enrollments declined by approximately 20% (King & Chen, 2025)—a troubling trend, yet one that is far less severe than in TEE. Several factors have contributed to this decline, including economic conditions, accountability and policy reforms, negative public discourse, and demographic changes. These forces have weakened recruitment pipelines, strained teacher preparation programs, and contributed to program closures. In TEE, these pressures are intensified by a longstanding lack of clarity regarding the field's mission and curricular identity.

Economic Factors. Much of the overall decline is due to factors beyond the control of preservice programs. Impacts of the 2008 recession constrained hiring and prompted higher education institutions to consolidate or eliminate low-enrollment programs, including many in TEE (Evans et al., 2019; Griffith, 2016). Rising student loan debt, increasing college costs, and stagnant teacher salaries widened the wage gap between teaching and comparable STEM fields, reducing the perceived return on investment for education degrees (Griffith, 2016).

Accountability, Perceptual, and Demographic Factors. Accountability reforms and student achievement–based evaluation systems have intensified professional pressures (Goldhaber & Knight, 2016), while alternative certification pathways have reduced reliance on traditional preparation programs (AACTE, 2022). Public regard for teaching has eroded amid critical media and political discourse (Cochran-Smith et al., 2022). Higher certification requirements, program consolidations, and demographic shifts—smaller college-age cohorts and increasing retirements—have further constrained the teacher pipeline, particularly in technical fields where industry wages are more competitive (Kraft & Bleiberg, 2021, p. 4; AACTE, 2024; U.S. Bureau of Labor Statistics, 2024).

Lack of Clarity of Mission. In addition to these factors, the decline must also be understood in relation to our field's longstanding struggle to articulate a coherent and widely accepted mission. We may take issue with Conant's criticism; however, there should be no argument that TEE's predecessor, Industrial Arts, articulated its mission clearly as "a study of the materials, tools, processes, and products of industry and their significance for society, designed to help all students develop insight and competence for living in a technological world" (Warner, 1947). There was no confusion as to Industrial Arts' place in the curriculum: a general education subject essential for preparing all students to live knowledgeably in an industrial world.

Today, while scholars in the field maintain that TEE is indeed a component of general education and provide accompanying rationales (ITEEA, 2020, p. 9), state policy structures often reflect a different orientation. Across many states, TEE is administratively housed within CTE rather than within general education, consistent with broader state approaches to organizing applied and workforce-aligned programs (Education Commission of the States, 2023). How TEE is positioned—as general education or as CTE—has profound implications for curriculum, instruction, assessment practices, teacher certification pathways, and public perception of the field.

Alternative Certification Programs. Some TEE scholars question whether preservice programs are truly declining when alternative, non-traditional pathways are considered (Love & Maiseroulle, 2021). Although these pathways do help supply teachers—approximately 39% of TEE teachers hold alternative certification (Bowen et al., 2019)—they often lack formal pedagogical preparation, resulting in challenges in lesson planning, classroom management, and differentiated instruction (Bowen & Williams, 2024). With fewer opportunities for peer interaction, alternative pathways impede development of a clear teaching identity. Accordingly, this paper focuses on declines in traditional, university-based TEE teacher preparation programs, recognizing a limited role for alternative routes as a means of bringing technically accomplished professionals—such as engineers—into the field.

Methodology

In this position paper, descriptive methods (Loeb et al., 2017) have been used to analyze TEE's mission, examine how the discipline has been positioned historically, describe long-term trends in undergraduate program decline, and interpret what those trends imply for the field's future. Historical data on undergraduate program numbers and degree production from 1990 to 2005 were obtained through a review of published literature and archival sources. More recent data, reflecting the status of undergraduate TEE programs as of 2025, were compiled through direct telephone conversations, Zoom meetings, and email correspondence with faculty, program coordinators, and institutional representatives. These data were used descriptively to document longitudinal trends and to contextualize the current condition of the field.

The analysis draws on a synthesis of foundational writings, policy documents, and peer-reviewed scholarship to identify themes related to mission clarity, general education status, and workforce alignment. Particular attention is given to contrasting historical critiques of industrial arts with contemporary formulations of TEE as a cognitively rigorous component of general education. Because the study is interpretive and descriptive in nature, its findings are intended to identify persistent tensions and inform professional dialogue, rather than to establish causal relationships or predictive models.

Discussion

The following sections address the disciplinary mission of Technology and Engineering Education and identify two strategic interventions that might strengthen and broaden pathways into the profession.

Grounding Our Mission in the Fundamental Purposes of Education

Grounded in first principles, the mission of TEE must be seen as integral to advancing the fundamental purposes of education. Most of us would agree that educators should strive to enable our students to:

- Respect and practice civility and ethical responsibility
- Maintain a lifestyle conducive to human well-being
- Earn a good living
- Question prejudices, misinformation, and propaganda
- Make a difference in the world
- Contribute to, adapt to, and benefit from technological change
- Derive optimal fulfillment from life's experiences

TEE's Unique Contribution to the Fundamental Purposes of Education

Although many school subjects support the broad aims of education, Technology and Engineering Education is uniquely positioned to advance several of these aims more directly and effectively. Because TEE immerses students in authentic design processes, problem solving, and engagement with real technological systems, it cultivates capacities that are difficult to develop in more traditional academic settings.

TEE classrooms require collaboration, respectful critique, and shared responsibility, allowing students to practice **civility and ethical responsibility** while working in teams within consequential contexts. Students explore technological systems that underpin human well-being, such as communication networks, energy production, and manufacturing. When TEE frames design challenges around societal needs—energy sustainability, food insecurity, potable water access, and aging infrastructure— learners see themselves as capable of **making a difference in the world**. Few other subjects provide such direct opportunities for students to apply knowledge in ways that can tangibly improve lives (NAE & NRC, 2002).

TEE develops competencies central to many high-wage STEM and technical careers, providing students with viable **pathways to earning a good living**. As students design fair tests, evaluate prototypes, analyze data, and judge claims against evidence, they learn to challenge assumptions and distinguish fact from opinion—skills essential for questioning **prejudices, misinformation, and propaganda**. Notably, TEE's most distinctive contribution lies in helping students **contribute to and benefit from technological change**. The engineering design-based pedagogy that is at the core of TEE instruction often evokes a psychological state of flow (Csikszentmihalyi, 1975, 1990), fostering intrinsic motivation and deep learning. Through hands-on modeling, iterative design, and system analysis, students develop the thinking skills needed to navigate—and influence—a rapidly evolving world.

The last goal—**deriving optimal fulfillment from life's experiences**—is often underestimated as a seminal purpose of education. An educated person sees things differently and appreciates them more than someone who has never been exposed to those facets of life. Being educated in physics helps one understand why a cyclist is advised not to ride against traffic flow; music education enables a deeper appreciation of performances seen and heard; and education in TEE allows one to see bridges (for example) very differently once they have designed, built, and tested them. Being able to value and appreciate what is encountered throughout life is a compelling argument for a solid liberal education for all learners.

Articulating the Disciplinary Mission of Technology and Engineering Education

Given the limited duration of course sequences typically available in middle and high school, Technology and Engineering Education cannot realistically assume responsibility for direct employment preparation. Rather, TEE assumes a clearly defined and unique role within every student's general education.

The position presented in this paper is that the mission of TEE should be: **To ensure a foundational level of technological and engineering literacy for all learners while serving as a feeder and pathway to community college and university technician and engineering education programs.** Positioned in this way, TEE complements postsecondary pathways that lead to occupational specialization and employment.

Suggested Interventions

Two complementary interventions are proposed to increase the number of TEE teachers and TEE teacher education programs. The first focuses on recruiting new teachers into the profession, while the second emphasizes curriculum modernization to enhance the relevance and broaden the appeal of TEE to prospective candidates. Together, these efforts warrant targeted changes to preservice education programs, ensuring that future educators develop the competencies demanded by today's technical workforce—particularly in computational thinking and statistical analysis.

Systematically Recruiting TEE Teachers

Declining undergraduate teacher education enrollment poses an existential threat to Technology and Engineering Education (TEE), making a coordinated national teacher recruitment strategy imperative. Three primary recruitment pools have the potential for promise: secondary TEE classrooms, community college (CC) programs, and student organizations such as the Technology Student Association (TSA).

TEE instructors engage hundreds of thousands of students each year, many of whom could become future teachers. Research shows that recruitment is most effective through personalized encouragement—particularly when a teacher explicitly affirms a student's potential (Love & Love, 2023). Given this, it is reasonable to ask whether a meaningful share of TSA's more than 300,000 student members might be attracted to teaching to share the skills and satisfaction gained through participation.

In response to the shrinking TEE teacher pipeline, a range of initiatives has emerged across school districts, higher education institutions, states, and national organizations. These include federally and state-supported programs such as Perkins V–funded "Grow Your Own" initiatives (TEA, 2020) and NSF-supported efforts like the Robert Noyce Teacher Scholarship Program, as well as local partnerships linking secondary schools, community colleges, universities, and workforce partners.

One illustrative example is the initiative led by the College of DuPage (COD) in Illinois, in partnership with Illinois State University and Valley City State University, which offers a clearly articulated pathway to a TEE undergraduate degree for CC students. Students complete the initial phase of their preparation at COD before transferring to either ISU or VCSU to complete a BS degree and certification requirements. Recruiting CC students offers strategic advantages: they often bring greater technical maturity, workplace experience, and diversity, with women comprising a majority of CC enrollees.

Building on the COD model, faculty teams from five university–community college–school district triads are pursuing NSF support as a consortium to scale this pathway nationally and adapt it across regional contexts. Titled Teach to Learn, Learn to Teach!, the project leverages a core educational principle: teaching deepens learning. As CC students explain technical concepts, anticipate misconceptions, and design instruction for secondary classrooms, they strengthen their own STEM understanding while experiencing the joy of teaching. With structured support from faculty and industry mentors, participants develop the pedagogical skills needed to inspire and sustain the next generation of the technical workforce.

Sustaining Curricular Relevance

To strengthen public support, expand student enrollments, and attract a broader pool of prospective teachers, TEE must reflect the technological realities that students, families, industry, and policymakers increasingly expect in contemporary schooling. At the same time, the field must overcome persistent perceptual barriers—particularly the widespread view of traditional technology education as shop-based, tool-centric, and male-dominated—that have constrained recruitment and public understanding. Integrating computer science (CS) into TEE provides a powerful mechanism for repositioning the discipline by connecting its long-standing design-and-construct pedagogy with digital technologies that define modern life, thereby enhancing relevance, visibility, and appeal to a wider and more diverse population of prospective educators

Digital literacy—including ethical and effective use of artificial intelligence—is now widely recognized as a foundational competency (CSTA, 2023, 2025; NAS, 2018). CS participation has grown rapidly, with a 1200% increase in middle school enrollments and a 248% increase in high school enrollments over the past two decades (Hacker, 2025). High schools in 32 states are now required to offer at least one CS course (Barack, 2025). Yet no single discipline "owns" CS instruction; it is taught across mathematics, business, computer science, and increasingly TEE—creating a strategic opportunity to strengthen and expand TEE programs.

Importantly, integrating CS into TEE is not a replacement for existing content, but an enhancement aligned with national priorities, workforce needs, and established TEE pedagogy. Since 2018, NSF-funded initiatives—including ExCITE I and II (NSF 1923552, 2318343) and Computer Science through Engineering Design in New York (CSED-NY, NSF 2341962)—have demonstrated that TEE teachers can effectively integrate CS through engineering design-based instruction. External evaluations (Hecht, 2024, 2025) indicate that students report high engagement when learning to code through the design and construction of authentic technological systems such as traffic lights, railroad crossings, roller coasters, robots, and automated candy dispensers using microprocessors, sensors, and output devices.

As schools continue to expand CS implementation strategies, Technology and Engineering Education must position itself as a natural and indispensable partner. High-quality curriculum is available gratis from CSED-NY (https://www.hofstra.edu/csed) and ExCITE (https://bjc.techlit.org/bjc-r). The pedagogy guiding these projects was deliberately designed to align with TEE's long-standing emphasis on hands-on instruction. Integrating CS into TEE offers several important benefits.

Benefit 1: Expanding K–12 Student Enrollments. Integrating CS into TEE connects design-and-construct experiences with digital technologies that define modern life. Students are drawn to technological topics that align with TEE's hands-on, problem-based ethos (Israel et al., 2020; Bers, 2021). CS integration also helps broaden participation in TEE, attracting more female and underrepresented students through creative, collaborative, and socially relevant learning (Google & Gallup, 2021).

Benefit 2: Revitalizing Teacher Education Programs. Integrating CS provides a strategic path to revitalize declining TEE teacher-preparation programs. Preservice male and female students value CS for its relevance, innovation, and career potential (ACTE, 2020).

Benefit 3: Aligning with Public Perceptions. A persistent challenge for TEE is the gap between scholarly definitions of technological literacy and public perceptions of technology as computing and digital tools. Integrating CS helps close this gap by connecting TEE with recognizable technological domains—computer systems, programming, robotics—enhancing visibility, relevance, and credibility among educators, parents, and policymakers.

Summary

The historical shift from industrial arts to Technology and Engineering Education represents not a retreat from general education, but an attempt to correct the weaknesses Conant identified. When TEE is framed around authentic design problems and situated within real technological systems, it enables students to understand how scientific principles, mathematical models, social values, and human needs converge in the engineered world. In this sense, TEE fulfills the very general education aims Conant sought—developing informed, critical, and capable citizens—through modes of inquiry that complement rather than duplicate the work of other core subjects.

Strengthening the discipline's place in schools will entail clarifying the general education disciplinary mission, emphasizing its place in the educational continuum in secondary and postsecondary education, and retooling curriculum so that design pedagogy, engineering thinking, and computer science/computational thinking are well integrated into instruction.

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His research centers on sustaining the relevance of Technology and Engineering Education, strengthening engineering design pedagogy, and embedding authentic societal challenges as meaningful contexts for instruction. Most recently, he has investigated the mathematics competencies technicians truly need to succeed in today's evolving workforce.