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From the Editor

Coalescence of a Field

It seems fitting that this, my final editorial, would address the issue of educational relevance which the profession has struggled with for as long as I have been a member of it. Specifically, this editorial explores what I perceive to be a transformation that may well be the harbinger for a long-awaited coalescing of our field. For decades, the academic domain tasked with promoting technological literacy and developing human capability in the designed world has been a discipline divided by geography, culture, and vernacular. Whether operating under the banner of Technology Education (TE) in some regions, Design and Technology Education (DTE) in the United Kingdom, or Technology and Engineering Education (TEE) in the United States, these subfields have long functioned in relative isolation, bound largely by a shared focus on material manipulation (the doing) but separated by distinct epistemological and philosophical traditions. This historical fragmentation often obscured the universal nature of what our educators might actually be observed teaching in their classrooms around the globe, leaving the profession vulnerable to shifting political whims and the uncertainties of educational identity.

Not intended to be an in-depth empirical investigation of this long-standing issue, this editorial draws on my own observations over the past four decades of trends in international research. Through my own personal lens, it appears that in recent years a strong undercurrent has been quietly and fundamentally reshaping what historically has been an internationally fractured discipline. The gradual confluence of research focused on the transdisciplinary cognitive demands of Technological/Engineering Design Based Learning (T/E DBL) has provided an empirical baseline that transcends regional culture and vernacular. By analyzing the immense mental modeling, metacognitive regulation, and heavy working memory demands imposed on learners navigating ill-defined design problems, international scholars have increasingly provided evidence that designing is a highly rigorous, universal cognitive architecture. This line of research has resulted in a growing consensus regarding the importance of cognitive research among our scholars, and catalyzing a profound shift in what we are choosing to substantiate our place in the educational landscape. Concurrent with this shift is the steady elevation of our discipline from disparate craft-based traditions into a more globally recognized field of academia.

This shared understanding is forging a powerful, unified identity. Specifically, it is a transition toward international solidarity that anchors our collective future not singularly in the hands-on (tool use) approach, but universally in the minds-on (use of tool) pedagogy of design based learning which teaches students to think critically, regularly engage in iteration as a method of refining concepts requisite for understanding, and then capitalize on

newly acquired understandings to conceive of satisficing solutions. Over the past several decades, this movement toward a unified academic identity has been heavily anchored in the cognitive architectures of T/E DBL. The impetus for this evolution, however, began quite some time ago.

Historical Fragmentation

In 1985 the change in name from Industrial Arts Education to Technology Education in the U.S. signaled a recognition in the profession of the need to keep pace not only with technological change, but with a changing educational landscape challenging the relevance of the discipline as a school subject. In the decades that followed, this context of technological and educational change brought with it, among other things, a need within the profession for a research agenda focused on legitimizing the field as a school subject.

Studies such as the one conducted by Foster in 1992 investigated the topics and methods of graduate student research as a plausible gauge of the direction of research in technology education. Results indicated that program evaluation, largely through surveys, was the most common topic and method. Not long afterwards, Zuga's 1994 analysis of research conducted between 1987 and 1993 in technology education found most were curricular in nature, with little attention focused on the intrinsic educational value of the field, its unique approach to problem solving, or the cognitive demands inherent with technological design. Several years later Lewis (1999) attempted to give focus to our research agenda by proposing potential areas of research that were "compelling because: (a) they relate fundamentally to the basic claims of the field, (b) they remind us that technology education ultimately is about learning and teaching and the primary actors in that enterprise must be brought into sharper focus, and (c) they share and conform to conceptual frameworks (such as situated cognition and constructivism) that unite technology education with other school subjects" (p. 43). More than the first two, it was his third point of using research to unite technology education with other subjects and focus on the cognitive benefits of T/E DBL that took root among the science, technology, and engineering education researchers. In the following decades, scholars in the U.S. and internationally increasingly prioritized investigations evidencing the link between intentional transdisciplinary learning in T/E DBL and the resulting cognitive benefit of enhanced conceptual understanding.

Confluence of Cognitive Research

In the years between 2000 and 2026, research focused on T/E DBL published in major technology and science education journals revealed a gradual transitioning away from curricular, skill-based (the doing) foci to those focused more on demonstrating cognitive connections and promotion of conceptual understanding. To highlight this transition, listed below are a select few authors who published research in a variety of research journals (full references

provided) during this timeframe directly or indirectly emphasizing connections between T/E DBL and conceptual understanding:

International Journal of Science Education – France, 2000
Journal of Technology Studies – Barak, 2000; Akpan, Etim, & Udoh, 2026
Journal of Industrial Teacher Education – Kolodner, 2002
Cognitive Studies: Kolodner, 2002
National Center for Research on Evaluation – Shavelson, Ruiz-Primo, Li, & Ayala, 2003
Journal of Research in Science Teaching – Fortus, et. al., 2004, 2005; Lewis, 2005; Puntambeker & Kolodner, 2005
Design and Technology Education: An International Journal – Norman, 2007; Atkinson & Davies, 2012; Chandrasekera & Mihandoust, 2020
Journal of Technology Education – Dunham, Wells, & White, 2002; Doppelt, et. al., 2008; Dixon & Johnson, 2012; Dixon & Lammi, 2014; Wells, et. al., 2016; Wells, 2010, 2016
Journal of Educational Technology and Society – Li & Tsai, 2007
International Journal of Technology and Design Education – Barak & Waks, 2000; Doppelt, 2009; Williams, 2011; Buckley, Seery, & Canty, 2018; Barak & Yuan, 2022
Journal of Curriculum Studies – Lewis, 2012
International Journal of STEM Education – Kelley & Knowles, 2016
Australasian Journal of Technology Education – Barak & Albert, 2017; Barak, 2020
Journal of STEM Education Research – Oner & Capraro, 2025

Similar trends can be observed in the published proceedings of key international conferences such as the PATT, ICTE, TENZ, etc. held between 2016 and 2026. A review of the proceedings from these conferences over the past decade reveals that a high percentage of papers are rife with research connecting T/E DBL with the development of higher order thinking, cognitive capabilities, and designerly knowledge acquisition. Furthermore, as demonstrated through the select sampling of participating institutes of higher education listed below, papers delivered at these conferences disseminate the research findings from scholars both within and outside of our profession hailing from countries around the world:

Australia (PATT: Australian Catholic University | TENZ: Curtin University; University of Sydney; Edith Cowan University | ICTE: University of South Australia; University of Melbourne)
China (PATT: Hubei University of Technology; Nanjing Normal University; Beijing University of Technology; Renmin University of China; Capital Normal University)

Germany (PATT: University of Koblenz; Carl von Ossietzky Universitat Oldenburg)
Ireland (PATT: Athlone Institute of Technology; University of Limerick; Technological University of the Shannon)
Japan (TENZ: Saitama University; Shiga University; Kanagawa University; Naruto University of Education; Hokkaido University of Education | ICTE: Shinshu University; Nara University of Education; Shizuoka University; Teikyo University; Oita University)
Netherlands (PATT: Delft University of Technology, University of Applied Sciences, Utrecht)
New Zealand (PATT: University of Waikato, Victoria University, Wellington; University of Auckland Waipapa Taumata Rau | TENZ: University of Auckland; University of Canterbury)
Norway (PATT: Oslo Metropolitan University)
Republic of Korea (ICTE: Chungnam National University; Kongju National University; Korea National University of Education | TENZ: Gyeongin National University)
South Africa (PATT: University of Johannesburg)
Sweden (PATT: Linköping University; KTH Royal Institute of Technology; Karlstad University; Halmstad University; Uppsala University)
Taiwan (PATT: National Taiwan Normal University; Shih Hsin University | ICTE: National Kaohsiung Normal University; TENZ: National Central University)
United Kingdom (PATT: University of Exeter, University of Sunderland, Liverpool John Moores University; Nottingham Trent University; University of Glasgow | TENZ: Goldsmiths, University of London)

Researchers presenting their findings at these conferences are not necessarily intentionally attempting to legitimize technology education (TEE or DTE) as a school subject, but their findings non-the-less provide evidence for legitimization. And that evidence resides within the common emphasis on demonstrating the value of imposed cognitive demands that are inherent to the T/E DBL approach. This growing body of empirical research is increasingly demonstrating that designing T/E solutions is not merely a procedural sequence, but a rigorous cognitive process. These scholars are documenting the high cognitive demands naturally imposed on learners as they navigate ill-defined problems, requiring concurrent management of working memory, transdisciplinary and domain-specific knowledge, and both physical and conceptual tool manipulation. The transition from isolated skill acquisition to design-based learning has resulted in a growing international focus on metacognition. Learners engaged in T/E DBL must constantly evaluate constraints, optimize solutions, and tolerate ambiguity, all of which require

cognitive behaviors that remain identical whether a student is in a TE/TEE/DTE program, or a program within one of the core sciences (physics, chemistry, biology, etc.).

Perhaps of greater importance, accumulated research establishes that technological literacy relies on specific designerly heuristics and a capacity for internal mental modeling. This empirical consensus is effectively shifting the international view of the field from a hands-on (doing) focus to a distinct, highly demanding minds-on (cognitive) discipline. This shared cognitive framework has been instrumental in facilitating international solidarity, and stimulating consensus regarding the universal underlying mental processes associated with the designerly way of coming to know. The gradual coalescing of the field over the last few decades reflects a move away from fragmented provincial identities toward a global community bound by a singular ontological truth: the field studies and develops human capability in navigating the designed world.

Toward a Unified Identity

As noted at the outset, this editorial is not meant to be a full research treatise empirically demonstrating a research trend. Instead, it presents the case for this trend based on decades-long personal observations of a field dedicated to promoting T/E DBL as the signature pedagogy, and the designerly way of knowing as a knowledge acquisition heuristic unique unto our field. It is from this vantage point that I contend there is a gradual converging of cognitive research internationally from our community of scholars that is ultimately investigating and documenting how engaging students in T/E DBL enhances their capacity to think critically. This shared research agenda marks a definitive shift away from the historical fragmentation that once siloed the profession to one gradually unifying as a field of academia identified by a pedagogy that intentionally capitalizes on the cognitive and iterative demands of technological and engineering design-based learning to enhance conceptual understanding.

Moving forward, this unified identity is affording the field the opportunity to speak with a collective, authoritative voice on the global educational stage. At the core of this identity is our unique approach to knowledge acquisition based on the heuristic of designerly ways of knowing. As we look to the future, our shared research infrastructure and conceptual alignment provide a robust platform to advocate for technological literacy of all learners in an increasingly complex, technological world. By celebrating our diverse regional histories while rallying around a singular, cognitively anchored identity, the profession is increasingly recognized as one that cultivates the critical thinkers, ethical designers, and innovative problem solvers tomorrow demands.

Coda: Change is the Only True Constant

"The universe is in perpetual flux; you can never step twice into the same river."

— Heraclitus, *Fragments*

Today, philosophically speaking, the idea that change is the only true constant is no more evident elsewhere than in the never ending process of technological change. We who are members of a field dedicated to promoting technological literacy are all too familiar with the impacts that constant technological advances have on society. One such technology that forever changed the world was the Gutenberg press invented by Johannes Gutenberg in the 15th century. The introduction of moveable type provided all of society with access to the printed word and the knowledge, perspectives, and insights those words conveyed. Today the Gutenberg equivalent is arguably the Internet which provides all of society with instant access to a global collective of information. The impact of this modern-day technological invention has been swift and far-reaching. One poignant example is reflected in the declining consumption of information presented through the printed word. Specifically, the demand for information in printed form is fading rapidly as the global society now prefers digital content that is accessible anytime and from anywhere.

The impact of this technological advance has spread far and wide, and in the scholarly realm it has resulted in a precipitous decline in the printed versions of our research journals. Like so many others, the *Journal of Technology Education* (*JTE*) is not immune to this decline in demand for printed journals. In fact, we are saddened to report that the number of subscribers to the printed version of the *JTE* has dropped to a point where the cost of producing the printed journal is no longer sustainable. In light of this, we have no options other than to follow suit with other research journals and move the *JTE* completely online in a digital version only. This issue, Volume 38, Number 1, will be the last hard-copy, printed version of the *JTE*. This issue of the *JTE* brings to an end a 38-year period of publishing the Journal in both print and online formats. Also coming to an end in 2026 is my role as the *JTE* Editor. As of this issue, Philip A. Reed, currently Associate Editor, will be transitioning into the role of *JTE* editor to begin January of 2027.

JGW

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Priming the design process to improve student learning

Nathan Mentzer, Abdul Moeed Asad, Wonki Lee, Andrew Jackson, & Scott Bartholomew

Abstract

Design thinking is critical in engineering and a fundamental for secondary students in introductory technology and engineering courses. The goal of this investigation was to measure impacts of a simple primer called Learning by Evaluating on students' design process. Students in introductory high school design courses were introduced to the primer as part of a treatment group. A comparison group did not receive the primer. Design documentation was collected in the form of students' design journals which were evaluated using a rubric. Results showed no significant differences in design journal scores between the group that received the treatment and the group that did not. While the primer did not result in measurable differences in design documentation, an interesting discovery emerged during the analysis. Design documentation, regardless of group, was not well aligned with standard practice. This discovery may warrant further investigation into how design documentation, a key design practice, is being implemented in classrooms and what kinds of support teachers may need to implement design with fidelity.

Key words: Comparative Judgement, Learning by Evaluating, design journal, design process documentation, design thinking

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Introduction

The need for high-quality STEM education has been well-documented by scholars and influential institutions, who argue it is essential for economic prosperity and an informed citizenry in these technologically-rich times (Jang, 2016; National Research Council, 2011; National Science Board, 2023). At an individual level, a strong STEM education foundation is essential for effective, evidence-based engagement in public discourse on critical scientific and technological issues (National Research Council, 2012). Beyond civic engagement, a STEM education sets students up for individual economic mobility and the nation for broader prosperity. According to the U.S. Bureau of Labor Statistics, STEM occupations are projected to grow at nearly three times the rate of other fields and offer higher median annual wages than that of non-STEM workers (Watson, 2025). At a national level, a STEM-trained workforce is crucial for maintaining a global edge in innovation (Jang, 2016), powering the

economic engine of a nation. Given these stakes, early and effective K-12 education is critical because research shows that a majority of students who pursue STEM careers make that decision during their secondary school years (Maltese & Tai, 2011).

The pressing need to improve STEM education requires the investigation of effective pedagogical strategies to better prepare students for an increasingly complex technological world. Accordingly, educators have moved toward teaching STEM education through a more cohesive, integrated approach that situates learning in authentic, applied contexts (Kelley & Knowles, 2016). Engineering design has emerged as a powerful catalyst for this integration, providing a natural framework for building connections among the STEM disciplines and earning a central place in national education standards (NGSS Lead States, 2013; *Standards for Technological and Engineering Literacy (STEL) (ITEEA*, 2020). However, the effective implementation of engineering design in the classroom remains a significant challenge. A consistent finding in the literature is that novice students struggle to engage in the design process as experts do, often rushing linearly through tasks and holding fundamental misconceptions about the nature of design (Crismond & Adams, 2012a; Mentzer et al., 2015). These struggles relate to both cognitive hurdles, such as underdeveloped problem-solving strategies (Crismond & Adams, 2012a), and affective challenges, such as a lack of self-efficacy in the face of the uncertainty inherent in design tasks (Cash & Kreye, 2018; Osmond & Tovey, 2015).

In response to the challenge of improving STEM education pedagogy by better supporting students' engagement with engineering design, this study investigates a pedagogical primer developed as part of a larger National Science Foundation funded project. This primer, known as Learning by Evaluating (LbE), engages students as judges of pairs of previous student work before engaging in similar work themselves as part of their current project. This design primer has potential to support novice designers to critically think about the nuances of what constitutes a good example of design work, thus actively engaging students in thinking about the nature of design as an intentional, thoughtful process that begins with a well-defined problem. In reviewing peer work, students may have a heightened sense of certainty that they too can be successful, which is especially critical for novice designers in open-ended ill-defined design tasks. With its foundation in cognitive apprenticeship and social constructivism, LbE has shown success in fostering student recognition of good design work and student design reasoning. Focusing specifically on secondary education, the current study builds on prior LbE research at both the middle school (Bartholomew, Strimel, et al., 2019) and university levels (Bartholomew et al., 2018; Bartholomew, Zhang, et al., 2019; Buckley et al., 2022; Seery et al., 2019; Seery & Canty, 2017).

The goal of this investigation was to empirically measure the effect of the LbE intervention on student learning and achievement within high school

engineering design classrooms. To that end, this study investigated the following research question: To what extent does the Learning by Evaluating (LbE) intervention impact student achievement in engineering design compared to standard classroom practice? This paper will review the relevant literature, present the research method and findings of this study, and discuss the implications of the results for technology and engineering education.

Literature Review

The Role of Engineering Design in STEM Education

The engineering design process is a complex cognitive activity including systematic and iterative activities to produce an output that satisfies requirements set by a client (Dym et al., 2005). The engineering design process stands as the central integrator of STEM education programs, with its significance recognized in integrated STEM academic frameworks (Kelley & Knowles, 2016), standards for technology and engineering (*Standards for Technological and Engineering Literacy (STEL)*, (ITEEA, 2020) and science education (NGSS Lead States, 2013) in the United States. The NGSS framework, a popular science education framework now adopted by 44 states (Next Gen Science, n.d.), identified engineering design across all three of its core dimensions, elevating engineering design as a fundamental element of STEM education (Moore et al., 2015). The emphasis on engineering design is reinforced by a pedagogical shift that moves from rote memorization of facts to a more process-oriented and problem-based approach to learning (NGSS Lead States, 2013). Beyond merely introducing students to subject knowledge, this movement signified a commitment to fostering essential 21st-century competencies, including systems thinking, creativity and collaboration because they are inherently practiced within the engineering design process (Lucas & Hanson, 2016; National Academy of Engineering & National Research Council, 2009). Thus, engaging in engineering design practices enables students to navigate an increasingly complex technological world.

The engineering design community has theorized that there are many classroom benefits attributed to engineering design, and particularly for the potential of integrated STEM education to improve student engagement in the pure sciences, increase overall learning and achievement, increase interest in the engineering profession, and improve technology literacy (Hill, 2006; Gattie & Wicklein, 2007; Feder et al., 2009). In the decades following the work of these scholars, there has been significant literature that has followed up on these claims (Sneider & Ravel, 2021) which has largely substantiated that the integrated teaching methods are more effective than traditional, siloed approaches. Sneider and Ravel (2021), in their systematic literature review, found that engineering design methods show their effectiveness with students self-reporting increased engagement in STEM education and better results in

standardized tests of science and mathematics. As students move through the iterative engineering design process, they build vital competencies for fostering innovation in professional engineering practice, referred to as the engineering habits of mind in the literature (Lucas & Hanson, 2016). These habits of mind include skills like system thinking, creative problem solving, collaboration and communication.

The Design Journal as a Tool for Authentic Assessment

Engineering design journals are used in engineering professional practice where, according to Kelley (2011), meticulous documentation is paramount. Due to the open-ended hands-on problem-solving emphasis of engineering design pedagogical practice in K-12 technology and engineering education, these journals are uniquely positioned instruments for authentic assessment in the classroom. They allow educators to evaluate the design process itself, not just the final outcome.

Much like professional engineers, students using design journals are tasked with chronologically recording their work. This documentation provides a comprehensive record of the design journey, encompassing background research, initial sketches, critical decisions, prototype evaluations, personal reflections, and iterative modifications (Kelley, 2011). To further mirror authentic engineering practices, students are often encouraged to follow professional conventions such as titling, signing, and dating each entry. The journal, therefore, becomes a compendium that prioritizes and makes visible the entire design process.

Building on this emulation of professional practice, scholars argue that design journals offer several distinct benefits for K-12 students. They are thought to foster metacognitive reflection, provide a rich source of data for assessment by making student cognitive processes visible, and instil good professional habits, such as refining communication skills and protecting intellectual property (Asunda & Hill, 2007; Hill, 2006; Kelley, 2011).

Current Challenges in Engineering Design Thinking Practices

While integrating subjects through engineering design holds immense promise for integrated STEM education, its classroom effectiveness may be contingent on proper implementation. To understand secondary student design thinking, Mentzer et al. (2015) compared the design processes of high school students with those of experts. Using an established protocol where participants designed a playground for a fictitious neighborhood, the researchers revealed that students tended to rush linearly through the critical early phases of problem-scoping and ideation. Experts, in contrast, dedicated substantially more time to these activities. This finding is consistent with a larger body of work by Atman and her colleagues (Atman et al., 2005, 2007), who used the same protocol to identify similar patterns between novice and expert designers at the university

level. This tendency to shortcut the design process is a key challenge for educators, and the literature suggests two primary explanations for it: one cognitive, rooted in student misconceptions about design, and the other affective, related to a lack of self-efficacy.

The cognitive explanation posits that students rush because they hold fundamental misconceptions about the nature of design itself. Design is not simply a linear procedure but a distinct way of knowing and reasoning (Cross, 2006). As Mentzer et al. (2015) showed, high school students have not developed the habits or expertise to operate at the cognitive level of experts. For example, according to Mentzer (2014), high school seniors' information gathering focused on solution-oriented information (e.g., information on material costs), instead of problem-focused information (e.g., community concerns) as experts' might. Mentzer's (2014) findings are consistent with Crismond and Adams' (2012) influential *Informed Design Learning and Teaching Matrix* that highlighted nine key ways novices misconstrue design practices, which are detrimental to the final output. The misconceptions identified by Crismond and Adams span the entirety of the design process, from framing problems to reflecting on the final output. For example, like in Mentzer et al.'s (2015) study, novice designers are known to skip early research in favour of moving directly towards the solution, leading to missed opportunities in understanding the problem and subsequently missed potential in the quality of the designed solution. It is important to find effective ways to address students' misconceptions because misconceptions can be persistent and interfere with learning (Smith III et al., 1994).

A second potential explanation for novices' struggles is affective, centering on the concept of self-efficacy – an individual's belief in their ability to successfully execute the actions required for a specific task (Bandura, 1977). When students have low self-efficacy regarding design, they are less likely to persist through challenges and more likely to avoid behaviors they perceive as risky, such as open-ended creative exploration. This lack of confidence in a design context appears to stem from two interconnected sources: students' perceptions of their own abilities and the inherent uncertainty of the design process itself.

First, a student's self-concept can directly influence their design behavior. According to a study by Fila et al. (2014), college engineering students did not see themselves as creative, seeing a creative identity as something separate from an engineering identity. This led them to avoid activities they considered to be creative and gravitate towards routine and already existing solutions. Second, design is famously an uncertain, ill-defined process (Cash & Kreye, 2018; Osmond & Tovey, 2015; Tracey & Hutchinson, 2016). This ambiguity can lead to feelings of anxiety, and manifest as premature narrowing of creative exploration and rushing towards a solution in the engineering design process. Because navigating this uncertainty is so fundamental to the discipline, some

educators consider it a *threshold concept* that students must grasp to truly understand and feel efficacious in design (Osmond and Tovey, 2015).

Learning by Evaluating as a Technique with Potential to Improve Student Learning Outcomes

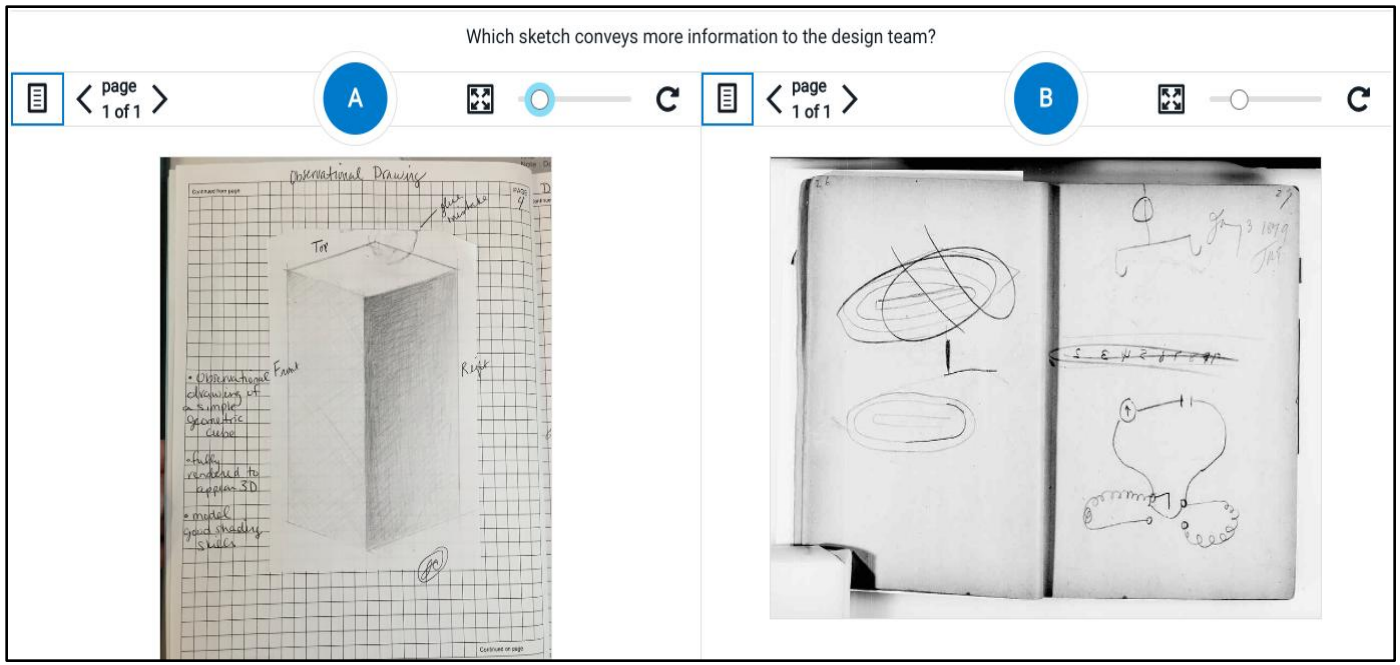
To address these challenges and improve student learning outcomes in engineering design, pedagogical strategies are needed that build student cognitive skills and sense of self-efficacy effectively. Learning by Evaluating (LbE) is a promising pedagogical technique hypothesized to achieve these goals because it is situated at the intersection of two powerful educational approaches: the use of exemplars and cognitive apprenticeship. This study, as part of a larger investigation into LbE, sought to understand its impact on student learning in an engineering design context (Bartholomew, Mentzer, & Jackson, 2022; Mentzer et al., 2024; Thorne et al., 2024).

LbE is a pedagogical technique used to prime students for learning experiences through several phases including conducting pairwise discrimination between exemplars based on a predetermined criterion (Figure 1). Comparison prompts are provided to the student by the instructor based on the learning objectives of the teacher (e.g., "which is a better problem statement?") and, following a series of individual comparisons, a classwide discussion reinforces students' understanding of quality design and equips them for project work. For examples of LbE sessions and findings related to students thinking as they engage in LbE, see Lee et al., 2024, 2025.

LbE works on the principle of comparative judgement to reduce the cognitive demands for students, allowing them to view multiple examples quickly. Comparative judgement is predicated on the fact that humans find it easier and are often more reliable when they are comparing two items side-by-side than when attempting to assign an absolute judgement to a single item in isolation (Bartholomew, Mentzer, & Jackson2022; Pollitt, 2012). LbE has shown to be beneficial in terms of elevating student learning for many disciplines including engineering design, English and business (Bartholomew, Mentzer, Jones et al., 2022).

Figure 1

Illustration of Pairwise Comparison in LbE Using RM Compare



Note. The RM Compare interface displays the comparison prompt at the top ("Which sketch conveys more information to the design team?") followed by each item. Once an item is selected, the judge is prompted to enter their rationale.

LbE Exemplars for Building Understanding

Students in an LbE experience view exemplars that are usually snippets of varying quality from iterations of similar, previously conducted projects. In an engineering design context, exemplars are usually items from student design portfolios or pictures of prototypes. Exemplars work in two major ways: (1) By viewing quality examples, students are able to witness for themselves what successfully fulfilling criteria looks like in practice (Sadler, 2002), better aligning expectations with that of the instructor and reducing the ambiguity of assessment criteria; (2), by viewing poor quality examples, they are able to see that their own initial ideas are not as far off as they might have feared, building the confidence to begin the task (Canty, 2012; Hawe et al., 2021).

A common concern of using exemplars is that they can inhibit creativity or encourage students to copy from what they observe. However, research suggests that these concerns can be mitigated by careful pedagogical design. Some strategies include having students evaluate a range of ways to approach the problem, using exemplars that are good but not perfect, and using exemplars that are analogous but not identical (To et al., 2022). In addition, the open-ended, ill-defined nature of design problems is an advantage here because there is not one correct answer, there are many potential solutions. Indeed, given the variety of criteria that might relate to a design context, different solutions may excel in different ways (e.g., an idea that is lightweight vs. one that is durable vs. one that is economical). Making this point clear by discussing tradeoffs in the context of prior work provides students and their teacher a chance to clarify design value structures before embarking on their project.

LbE as a Form of Cognitive Apprenticeship

Cognitive apprenticeship can help students develop the cognitive skills necessary to engage in the engineering design process (Jackson & Strimel 2018). According to cognitive apprenticeship theory, developed by Collins et al. (1991), students gain expertise by observing and reflecting on the knowledge of others, including experts and peers (Collins, n.d.). The emphasis of the technique is to make thinking visible, allowing learners to access the tacit knowledge that guides expert performance. This model is particularly pertinent to open-ended disciplines like engineering design where problem solving is complex and solutions are not predetermined (Collins et al., 1991).

The LbE process can be framed as a powerful form of cognitive apprenticeship. The model of cognitive apprenticeship outlines six key teaching methods: modeling, coaching, scaffolding, articulation, reflection, and exploration. LbE directly engages three of these core methods (Bartholomew et al., 2024; Thorne et al., 2024). When students examine a pair of exemplars, they are going through the *modeling* phase of cognitive apprenticeship by observing how others perform a task. The act of making a judgment forces them to engage in *reflection* by having them compare the two artifacts against their own internal

understanding of quality, improving their personal mental models surrounding the task. Then, as they write the reasoning behind their choice, students engage in *articulation*. This act helps make their tacit knowledge explicit, which can lead to deeper understanding. Finally, students have the opportunity to test their ideas in a teacher-led debrief about why certain exemplars were ranked higher than others. This process externalizes their own thinking, allowing it to be examined, challenged, and refined through dialogue with peers and the instructor.

Method

Research Design

This study is part of a larger study on Learning by Evaluating involving multiple schools and teachers. However, the present study examined artifacts from only two teachers in the district. We selected these two teachers because we found that teachers in these classrooms were most consistent in expecting students to document design process work in their journals, allowing us the opportunity to analyze the quality of students' design thinking.

Our research followed a quasi-experimental nonequivalent treatment and control group design in order to make causal inferences about changes to student learning associated with the LbE experiences. Each technology and engineering education (TEE) instructor taught at least two sections of an introductory TEE course called Foundations of Technology. In our study, we randomly assigned treatment and control conditions to each teachers' classroom. Therefore, each instructor contributed both treatment and control students for this study. Instructional procedures which differed between these conditions are described later. To mitigate the potential for selection bias inherent to quasi-experimental nonequivalent treatment and control study designs, as described later we also measured our sample students' performance at the start and end of the term to increase internal validity (Shadish et al., 2001).

Curriculum Context

The International Technology and Engineering Educators Association (ITEEA) offers nationally and internationally disseminated curriculum and teacher professional learning opportunities. The association's introductory high school course is called Foundations of Technology (Gensemer & Caron, 2010). The study took place within this course. Foundations of Technology is centered on a series of iterative design cycles; in each, students work individually or in teams to design, build, test, refine, and finally present a solution to a design challenge. For example, one unit challenges students to improve a community park while learning computer-aided drafting (CAD) software. Instruction begins with students learning about CAD features and commands. Then, the class identifies a community park to analyse and improve. Students document their work in an engineering design journal (e.g., researching the problem, imagining

solutions, and so on) including design drawings and a write-up about the park improvements.

In this course, students are expected to keep a design journal documenting their design process. While design solutions, often products, are the focal culminating result of student work, the course learning objectives and content foster development of students' ability to work through a structured, iterative design process. Students' design journals are not only valuable for students to document their work for future reference and reflection, but as windows into student thinking processes for assessment purposes.

Procedure

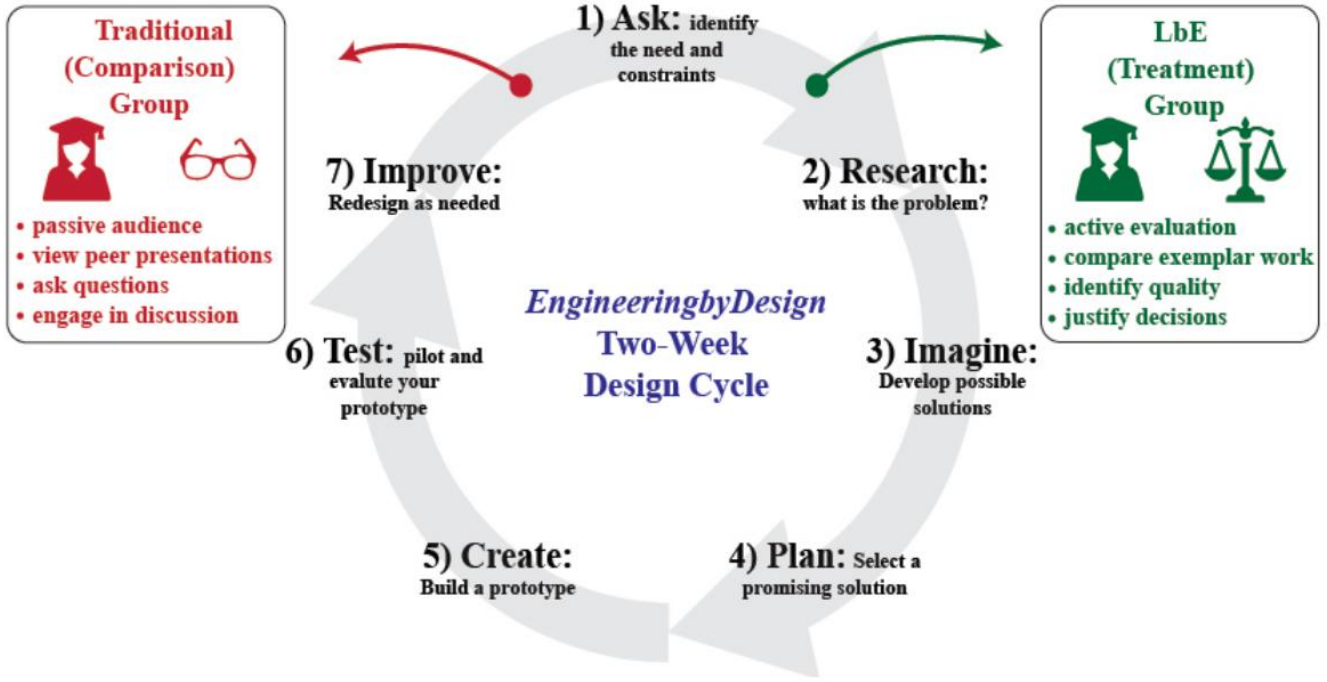
The teachers worked closely with the research team to foster fidelity of implementation and researcher awareness of curriculum in situ. Teachers were engaged in professional development on LbE annually in the form of a one day in person group meeting. In addition, teachers met with the research team at field based conferences, during observation visits and virtual visits throughout the year. The research team observed classrooms approximately monthly, engaging in the consent process as well as noting teacher strategies and offering support.

Control Group

The control group followed a traditional design cycle as shown in Figure 2 with a culminating report out, and often a peer presentation experience, as the final activity of the design cycle. These commonly took the form of a classwide presentation by each design team about their process, or a design report submitted to the teacher. These peer critique presentations gave students an opportunity to see others' work and engage in discussion around the process and solutions as a culmination of the design challenge or unit of instruction.

Figure 2

Illustration of the Differences Between Control and Treatment Curriculum Design



Treatment Group

In contrast, the treatment group participated in Learning by Evaluating (LbE) experiences at the start of a design cycle as shown in Figure 2 to prime students for the learning experience ahead. Not only did teachers use LbE at the start of the project, they also used it at the start of specific phases of the design cycle, such as problem definition or brainstorming. The LbE experience can be completed quickly (e.g., 10-15 minutes) and as alluded to in the literature review, is structured into three distinct phases:

Phase 1: Introduction and Orientation (Whole Group)

In the initial phase the teacher introduced the LbE session and oriented students to its learning goals. Sessions were created to fill in important gaps in student understanding as identified by the instructor and were aligned with the teacher's learning objectives. These objectives informed selection of exemplars and the creation of a specific comparison prompt that guided student judgments. For instance, if the objective was to improve prototyping skills, the instructor used images of prototypes on a similar project and constructed a comparison statement which might be as simple as, "*Which solution is better? Why?*" For a more targeted focus, such as structural integrity, the prompt could be refined to, "*Which solution can hold the most amount of weight? Why?*" During the introduction, the teacher often modeled the evaluation process by thinking aloud while making a comparison, or by leading a classroom discussion on the goals of the session (e.g., "*what are we looking for when judging structural integrity?*"). This modeling aimed to build students' capacity for critical evaluation and articulated reasoning (Jackson et al., 2022).

Phase 2: Individual Pairwise Comparison (Individually done on RM Compare)

In the second phase, students individually engaged in a pairwise comparison activity using the comparative judgement software *RM Compare* (RM plc, 2025). RM Compare software offered a secure online comparison system that harvested student activity data (individual student selection choices, comments, and class rank order). Students were presented with pairs of examples and tasked with determining which was superior based on the provided comparison prompt. A key component of this phase was the requirement for students to articulate the reasoning behind their decisions, thereby fostering critical thinking and engagement. As students in the class made selections, the RM Compare platform algorithmically generated a rank-ordered list of the examples based on the collective judgments.

Phase 3: Debrief and Reflection (Whole Group)

The final phase consisted of a whole-group reflection session led by the teacher, designed to facilitate the sharing of student thinking and to converge on a

common understanding of success criteria. During this debrief, instructors had the opportunity to reinforce key concepts and address any emergent misconceptions. The rank-ordered list generated by RM Compare often served as a focal point for discussion. Teachers typically used the highest-ranked examples to explore the qualities that constituted excellence, and the lowest-ranked examples to clarify common pitfalls and areas for improvement. This reflective discussion provided students with an opportunity to refine their mental models of high-quality work in preparation for embarking the project (or next phase of the project).

Data Collection

Data for this study were collected during the 2023-24 and 2024-25 academic years. With IRB approval, all students enrolled in the foundational course were invited to participate. Assent was obtained from all participants, as well as parent/guardian consent. Students were given the option to provide demographic data, including their race, gender, class year, and any prior experience in engineering or technology courses. A full summary of participant demographics is provided in the next section. At the conclusion of each academic term, researchers visited the classrooms to scan the physical design journals of all consented students. Digital scans of the journals were immediately uploaded to a secure, password-protected cloud server, and redacted prior to analysis.

Participants

This study was conducted in partnership with a large, diverse urban school district in the south eastern part of the US. The district serves over 100,000 students across more than 125 schools with a student population that is predominantly from underrepresented minorities in STEM fields (63.9% Black, 16.7% Hispanic, 11.0%, White, 6.4% Asian/Pacific Islander). Both teachers involved in the study had prior professional development in TEE and the LbE approach, as part of the larger ongoing project, and had previously taught the introductory course. The student population within their classrooms reflected the diversity of the broader district (see Table 1). One hundred and eighty-eight students had the opportunity to participate in the study but securing student and parental consent was challenging. The overall consent rate was 36.2%, with 17 students in control group classes and 36 in treatment group classes.

Table 1

Participant Demographics by Experimental Group

	Treatment (*n* = 36)		Control (*n* = 17)		Full Sample (*n* = 53)	
	n	*%*	*n*	*%*	*n*	*%*
Gender						
Male	17	47.2	14	82.4	31	58.5
Female	15	41.7	3	17.6	18	34
Non-Binary	0	0	0	0	0	0
No response	4	11.1	0	0	4	7.5
School Year						
Freshman	19	52.8	6	35.3	25	47.2
Sophomore	8	22.2	7	41.2	15	28.3
Junior	1	2.8	2	11.8	3	5.7
Senior	4	11.1	2	11.8	6	11.3
No response	4	11.1	0	0	4	7.5
Race						
Hispanic or Latino	10	27.8	7	41.2	17	32.1
White	15	41.7	2	11.8	17	32.1
Asian	3	8.3	4	23.5	7	13.2
Black or African American	2	5.6	2	11.8	4	7.5
Other or unknown	0	0	2	11.8	2	3.8
More than one race	1	2.8	0	0	1	1.9
American Indian or Alaska Native	1	2.8	0	0	1	1.9
No response	4	11.1	0	0	4	7.5
Prior Technology Experience						
No	30	83.3	14	82.4	44	83
Yes	2	5.6	3	17.6	5	9.4
No response	4	11.1	0	0	4	7.5

Of the participating students, 58.5% self-identified as male, 34.3% as female, and the remaining 7.5% did not respond to the question. The control group consisted of substantially more male students than female students. As expected for the introductory course, participants were primarily underclassmen, with freshmen (47.2%) and sophomores (28.3%) comprising the majority. The remaining consisted of juniors (5.7%), seniors (11.3%), and those that did not respond (7.5%). The largest proportion of students identified as Hispanic or Latino and White with each comprising around a third of total students (32.1%). Asian students were the third largest group making up 13.2% of the study sample. Proportionally, the treatment group had four times as many White students while the control group had twice as many Asian students. About a tenth of students (9.4%) had experience with TEE courses in the past, but most indicated they were taking a TEE course for the first time (83.1%).

Data Analysis

Measurement Instrument

Student performance was measured using a rubric produced as part of a previously funded $1.7M NSF DRK12 Grant (#1316601) project titled Engineering for All (EfA). The EfA design journal rubric was created to measure design practice standards that were rated by experts as *feasible*, *important*, and *clearly written* in the previous study (Lomask et al., 2018). In our study's context, the EfA rubric was in close alignment with the design process and expectations associated with the International Technology and Engineering Educators Association (ITEEA) Foundations of Technology course for classroom assessment. Therefore, we expected direct alignment between how students are evaluated in their courses and how their learning was measured in this research. The rubric used in this study for measuring student performance can be found on the EfA design project's website (https://www.hofstra.edu/stem-research/engineering-for-all.html).

The rubric consists of *nine criteria* that assess the engineering design process: (1a) *stating the design challenge*, (1b) *clarifying criteria*, (1c) *clarifying constraints*, (2) *research and investigation*, (3) *generating alternative solutions*, (4) *choosing and justifying the optimal solution*, (5) *developing a prototype*, (6) *testing and evaluating the design solution*, and (7) *redesigning the solution*. Each criterion was scored on a 3-point scale, which we modified to be a 4-point scale by including a zero level to explicitly account for students who did not attempt the criteria even though it was expected. The original scale was scored with a 1 where the performance was below expectation and "needed improvement", a 2 for "acceptable" work that was at expectation for the criteria being measured and a 3 for "really done well" such that the student had exceeded expectations. Each of the 9 criteria had additional context specific definitions for the scores 1, 2 and 3.

The primary outcome measure for this study was the overall project-level rubric score, calculated for each design journal by isolating a project, scoring it, and averaging the results of the scorable criteria. Although teachers for this study were chosen based on the general level of documentation in their classes, we found differences in which design documentation elements were required in each class. Therefore, when criteria have missing data, we chose to use available criteria when calculating the rubric score (not all 9 criteria). Average scores of available criteria were used to enable comparisons between pre- and post-measures and between control and treatment conditions. While project-level scores were used to test the main hypothesis, criterion-level averages are also reported in the findings section to illuminate student performance on each criterion and highlight what each criteria measured.

To obtain pre- and post-intervention scores for each student, we analyzed design journals from two separate projects selected based on included dates and chronological order. The pre-test score was derived from the first substantial project of the course which was either a pin design and a crane design. The post-test score was derived from the final substantial project which was either a fidget spinner or a bridge design. For our investigation, a *substantial project* was defined as one spanning at least two weeks, distinguishing it from shorter (one day), introductory exercises.

Interrater Consensus

To ensure calibration and reliability of scoring with the rubric, a multi-phase process was implemented. Two authors independently scored the same 4 design journals representing about 7.5% of the sample. Inter-rater reliability for the rubric scores was assessed using a two-way random-effects, absolute agreement, average-measures Intraclass Correlation Coefficient. The ICC was .57, $F(35, 35) = 2.43$, $p < .005$, 95% CI [.17, .78] which was considered moderate agreement. The researchers then discussed and negotiated any scoring discrepancies to consensus. Notes taken during this process led to an annotated rubric with documented details to clarify the operational definitions of each score category and to standardize the handling of atypical student journal entries. For example, an annotation was made for Criterion 7 (*Redesign the Solution*) to specify that qualitative data could be considered equivalent to *quantitative data* (specified in the original rubric) for a score of 3, which better aligned with teacher expectations of student work. A second round of independent scoring was conducted using 4 additional journals (7.5%) and, again, discrepancies were negotiated and documented. The ICC was .83, $F(35, 35) = 5.91$, $p < .001$, 95% CI [.67, .92] which was considered good agreement. At this point, the authors agreed the consistency between them was sufficient to have one author, blind to the treatment/control condition of each journal, code the entirety of the data set.

Findings

The findings are presented in two parts. We begin with the project-level analysis to investigate design documentation of students in the control group compared to those in the LbE treatment using gains from pre-to-post measures. Then, we present descriptive scores on each of the 9 rubric criteria to provide context and a more nuanced understanding of student design documentation.

Project-Level Analysis

To address our study's driving research regarding measurable learning gains related to LbE experiences, we conducted a repeated measures ANOVA using gain scores between the pre- and post-measures of student design documentation. Descriptive statistics show a modest increase in mean scores for both groups over the course of the study. The Treatment Group (n=36) saw their mean score increase from 2.20 to 2.34. The Control Group (n=17) saw their mean score increase from 1.97 to 2.23.

Prior to a repeated measures ANOVA, data were checked for normality using a Shapiro-Wilk test due to the small sample sizes. Pre- and post-scores were both found to deviate significantly from normal distribution. Therefore, we examined the Greenhouse-Geisser measure of Sphericity. The epsilon values were 1.000 indicating that Sphericity Assumed univariate test results were appropriate for interpretation of the repeated measures ANOVA tests. Effect size interpretations were based on Cohen (1988) partial η2 values of small, medium, and large as .0099, .0588, and .1379, respectively.

The analysis revealed a statistically significant main effect of time indicating that students' scores improved significantly between the first measure and the last, $F(1, 51) = 5.635$, $p = .021$). The effect size, partial eta squared (ηp^2), was 0.099, indicating the measure of student learning showed a small effect. Though the effect was small, the significant gains align with the course goals and lend credibility to our measurement strategy as teachers were strategically targeting learning of the design process which was measurable with our data and instrument.

However, the analysis of the time-by-condition interaction effect was not statistically significant, $F(1, 51) = .466$, $p = .498$ with a negligible effect size of .009. This crucial result indicates that the change in scores over time for the LbE treatment group was not significantly different from the change in scores for the control group. Thus, the treatment did not have a measurable impact on learning.

In summary, while students' design journal scores improved, these findings show no statistical evidence that the Learning by Evaluating treatment was more effective than standard classroom practice in producing this improvement.

Criterion Level Results

While the overall statistical analysis showed no significant treatment effect, examining the results at the criterion level reveals a more detailed picture of

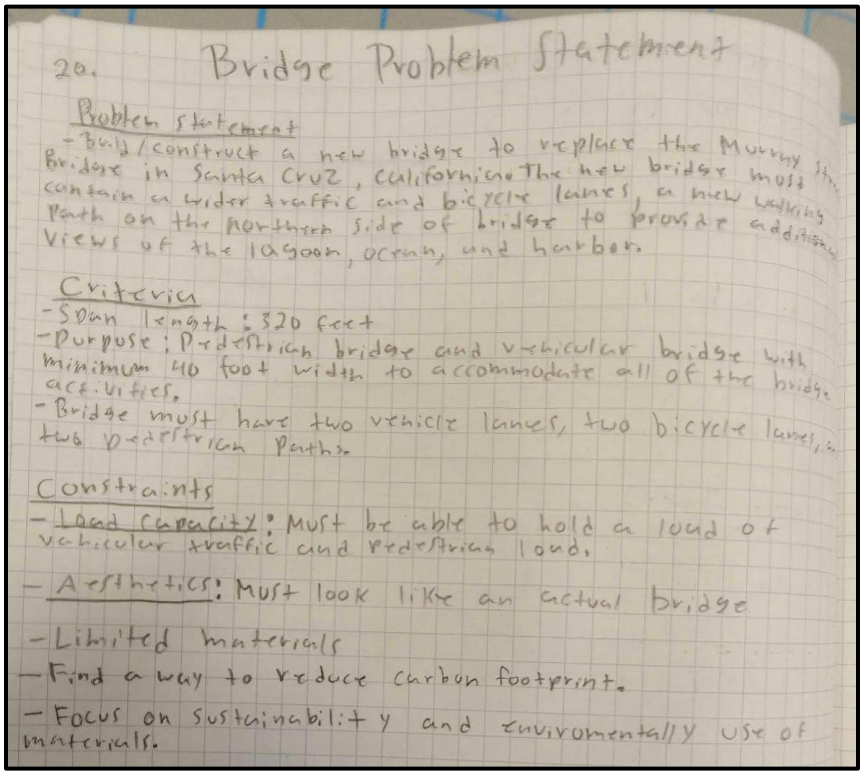
student documentation performance. The following section provides a descriptive breakdown of the pre- and post-test scores for each individual criterion, highlighting specific patterns of change and makes explicit our interpretation of the rubric.

Criterion 1a: Stating the Design Challenge

An example of the first several criteria is shown in Figure 3. For this criterion, the pre-score mean was 1.87 (n=53) and post-score was 1.81 (n=53), indicating very slight loss during the course. Most students received a score of 2 ("Acceptable") by restating the design challenge as it was provided by the instructor.

Figure 3

Example of Student Design Journal with Criterion 1a (Stating the Design Challenge), 1b (Clarifying Criteria) and 1c (Clarifying Constraints)



To achieve a score of 3, according to the rubric, students needed to frame the challenge in a way that also explained the underlying need for the work. Only four students, all of whom were in the post-test group, achieved this score. For example, one student who earned a 3 wrote:

> Build/construct a new bridge to replace the Murry Street Bridge in Santa Cruz, California. The new bridge must contain wider traffic and bicycle lanes, a new walking path on the northern side of the bridge to provide additional views of the lagoon, ocean and harbor.

The inclusion of the rationale (the need) for the new features that went beyond what was provided by the instructor, "provide additional views of the lagoon, ocean and harbor", differentiated the level of performance as "Really Well Done".

Criterion 1b: Clarifying Criteria

A noticeable improvement was observed for Criterion 1b, with the mean score increasing from 1.58 (n=53) in the pre-test to 2.55 in the post-score (n=53). An observation while scoring was the frequent confusion between design criteria and constraints. For instance, one student listed *load capacity*, *aesthetics*, and *reducing carbon footprint* under the constraints section (see Figure 2), when these are all performance criteria. Conversely, the same student listed *span length* and specific requirements like *two vehicle lanes* under the *Criteria* section, when these actually function as constraints on the design.

For purposes of this research, we focused on the existence of criteria regardless of them being categorized as criteria or constraints. Despite this, many students in the pre-test still struggled to identify any criteria, leading to scores of 1 (*Needs Improvement*). To receive a score of 2 (*Acceptable*), according to the rubric, students were required to state two distinct criteria for their design. A score of 3 was awarded to students who identified multiple criteria. The notable increase in the post-test score indicates that over the course of the intervention, students became significantly more adept at identifying and articulating the desired attributes of their designs, even if the formal distinction between criteria and constraints remained a point of confusion.

Criterion 1c: Clarifying Constraints

For this criterion, students began with a high level of proficiency that improved slightly, with the mean score increasing from 2.30 (n=53) to 2.55 (n=53). As mentioned, students often confused constraints with criteria; however, our scoring protocol awarded credit for the existence of constraints regardless of how they were labeled.

To score a 2 (*Acceptable*), students only needed to identify one constraint. Despite this relatively low expectation, a small number of students scored a 0 for not attempting the criterion or a 1 for failing to identify any constraints. Yet, an interesting discovery on this criterion was a pronounced ceiling effect. The median score for both the pre-test and post-test was 3, indicating that the majority of students successfully identified multiple constraints and earned the highest possible score from the outset.

Criterion 2: Research and Investigation

The mean score for this criterion showed a slight increase, moving from 1.63 in the pre-test (n=30) to 1.70 in the post-test (n=53). The discrepancy in sample size was due to one instructor's students not documenting parts of their project, rendering their pre-test journals unscorable on this criterion. However, the broader inclusion of this documentation following the introductory course is indicative of increased sophistication with students' design thinking and documentation in general. Students' research and investigation for both teachers' projects included students entering a list of *research questions* in their design journals and then using internet searches to answer them with occasional citations documenting sources.

A notable finding from the data was the prescriptive nature of the student work. Journal entries were highly uniform within classes, suggesting that the format was heavily guided by the instructor. In one teacher's post-test project, for example, all students documented their research by posing exactly five questions to be answered. This templated approach meant that most students achieved a score of 2 (students completed the pre-design tasks), perhaps just because they followed the teacher's requirements.

The primary differentiator for scoring was the quality of the research questions. Students scored low on the rubric for including questions that were not directly useful for constructing their prototype. Questions like *What is [the product]?* were regarded in our scoring as unhelpful, as it targeted general information students should have already known and therefore scored a 1 indicating students had not completed the research as a pre-design task. In contrast, questions such as, *What makes [the product] function well?* was considered helpful for informing the design and was therefore regarded as *completing research as a pre-design task*. To achieve a score of 3, students needed to do additional research that informed their design solutions which was interpreted as going beyond the teachers' expectations.

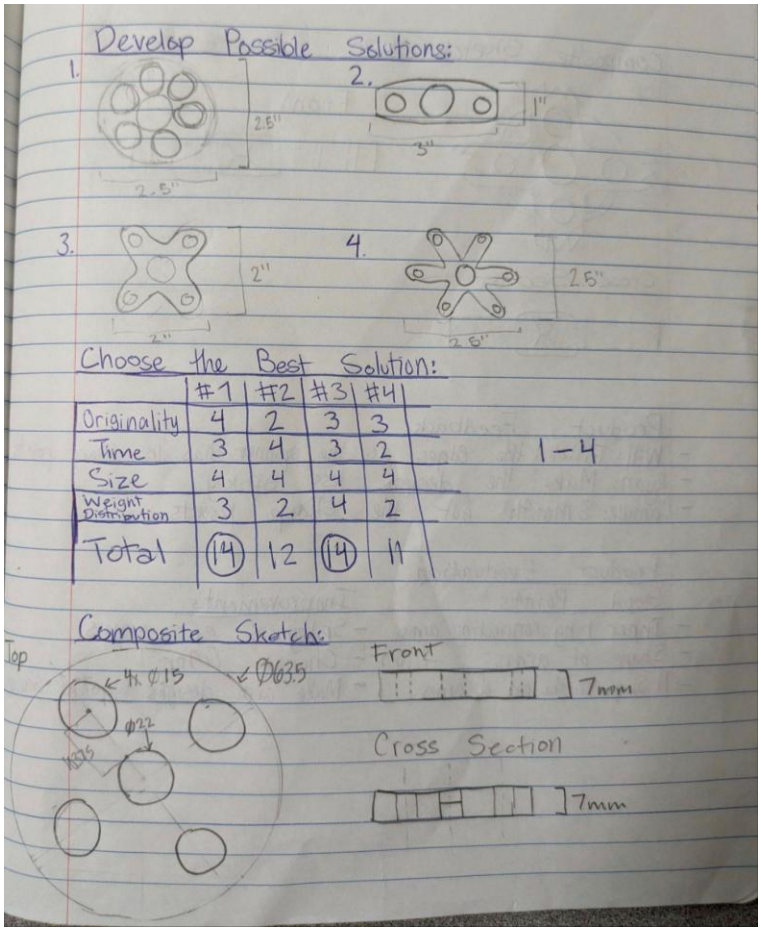
Criterion 3: Generate Alternative Solutions

The mean score for this criterion was high for both pre- and post-tests, showing a slight decrease from 2.97 (n=30) to 2.77 in the post-test (n=53). As with criteria 1c, we observed a strong ceiling effect, with most students achieving a score of 3. To earn this maximum score, students needed to show

evidence of an iterative process (Figures 4 and 5), by brainstorming multiple distinct solutions and then presenting a final sketch that differed from their initial ideas, therefore showing iteration. A score of 2 was given if students did not show clear evidence of this iterative problem-solving but did have a few ideas. A score of 1 was designated for students who only presented a single design without considering alternatives; notably, no student received this score in either the pre- or post-test.

Figure 4

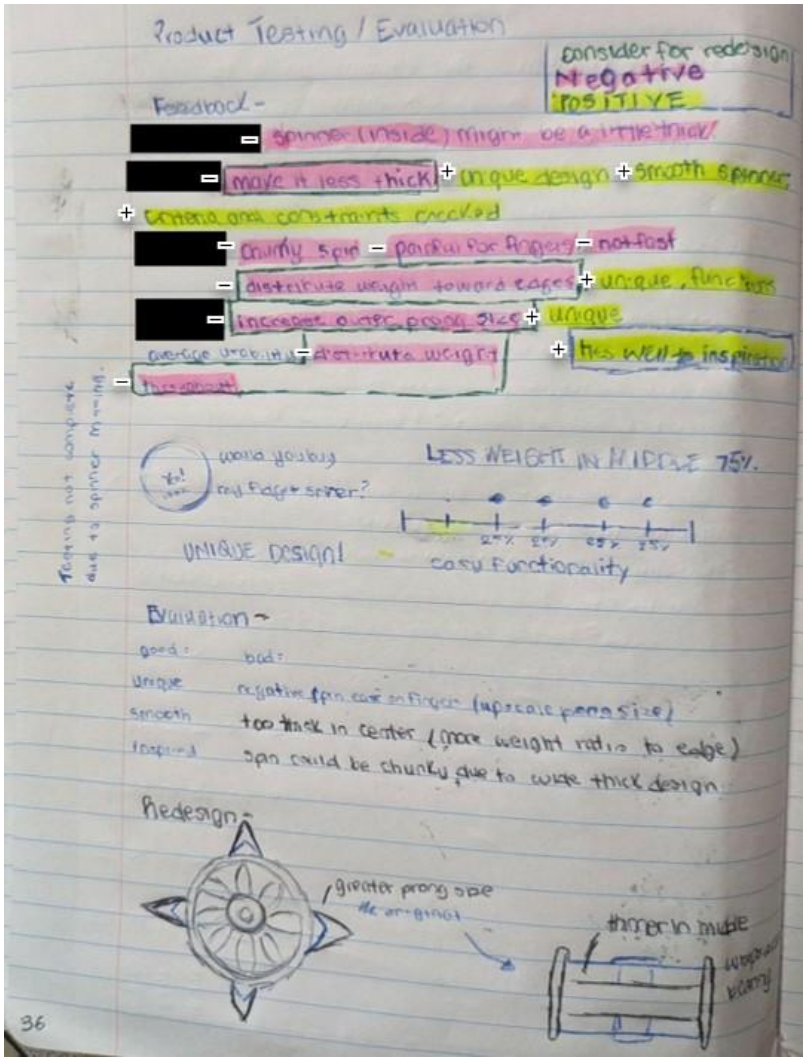
Example of Iterative Sketching in Design Documentation



Note: A student brainstormed 4 initial designs and created a different final sketch after evaluating all of their ideas earning them a 3.

Figure 5

Example of Iterative Sketching in Design Documentation



Note: A student collected feedback from their peers (names redacted) on their prototype and has highlighted them as "positive" (yellow) and "negative" (pink) using a marker followed by a redesign which differed from their initial ideas (not shown) resulting in a score of 3. To distinguish between peer feedback of student work in the black and white print copy, the authors have added (+) to indicate positive and (-) to indicate negative to the left of each item of feedback.

Criterion 4: Choose and Justify the Optimal Solution

The mean score for this criterion was also high, increasing from 2.33 in the pre-test (*n*=30) to 2.51 in the post-test (*n*=53). Performance levels on the criterion required a decision with justification for the highest score, while limited justification warranted a 2, and a lack of discussion earned a score of 1. Students who had no clear evidence of making a choice earned a 0. Surprisingly, scores on the criterion were bimodal, due to the common use of a decision matrix by students. This meant that students either had a matrix, which facilitated justifications and decisions, to earn a 3 or didn't have any evidence of making a decision and earned a 0.

As researchers, our evaluation of the quality of reasoning around the matrix was limited. The rubric only required the presence of quantitative measures. Further, the ambiguity of student-written labels would have made subjective quality judgments difficult, though perhaps deeper exploration of student decision processes would reveal differentiators in student learning. An example of a decision matrix can be seen in Figure 4.

Criterion 5: Develop a Prototype

A notable decrease was observed for this criterion, with the mean score dropping from 2.85 in the pre-test (n=53) to 2.36 (n=30) in the post-test. This decrease was primarily driven by a lack of documented evidence of prototyping in the post-test journals from one instructor's classroom.

The scoring for this criterion was largely based on completion. The rubric required a *representation* of the prototype (such as a final design sketch) for a score of 2, and evidence of a *working model* for a score of 3. As very few students included photographic evidence of their prototypes, we inferred that a working model had been created if the student included testing-related data from their prototype teaching in their journal. If testing data were absent, students with a final design sketch received a score of 2. The limitations of this inferential approach are elaborated further in the discussion section.

Criterion 6: Test and Evaluate the Design Solution

The mean scores for this criterion were high at the start of the term and end, showing a slight decrease from 2.58 in the pre-test (*n*=53) to 2.47 in the post-test (*n*=30). The high scores were attributable to the prescriptive nature of the testing procedures. In the projects we observed, all students appeared to perform the same pre-determined tests, likely assigned by the instructor. Consequently, students who documented the completion of this required test, which was considered a *fair test* by the rubric and analyzed these results to determine strengths and limitations, received a score of 3. Students who had no documented testing data, received a score of 0. Still, this bimodal scoring pattern produced a high overall average.

Criterion 7: Redesign the Solution

A noteworthy increase was observed for this criterion, with the mean score rising from 1.55 in the pre-test (n=53) to 2.13 in the post-test (n=30). This improvement reflects students' increased ability to justify their design modifications. To achieve a score of 3, students were required to articulate the reason for their redesign by explicitly referencing quantitative data from their testing phase (Criterion 6). To allow for variations in projects, we also interpreted sufficient qualitative feedback to serve as valid data for criterion (see Figure 3 for an example of a student that earned a 3). Students who proposed a redesign but did not connect it back to their testing results received a score of 2.

Discussion

The results of our study indicated that Learning by Evaluation (LbE) treatment did not produce a statistically significant change in student achievement. This finding is unexpected, particularly given the robust theoretical foundations of the intervention and the past research which has consistently demonstrated significant positive outcomes from LbE application (Bartholomew, Mentzer, Jones, 2022). This section will rationalize why this result is surprising by examining the established literature on the core components of LbE and then explore potential alternative explanations for our findings.

Our expectation that LbE would positively impact student achievement was grounded in well-established educational theories. The integration of exemplars into a curriculum, a key feature of LbE, has been theorized to enhance student achievement by fostering self-regulated learning (To et al., 2022). In a systematic study on the use of peer exemplars in technology and engineering education, Thorne et al. (2024) identified multiple benefits that lead to enhanced learning, including improved student focus, increased motivation to learn, the development of self-efficacy, and a higher standard for learning outcomes. Similarly, the principles of cognitive apprenticeship have been validated by over three decades of scholarship, which consistently demonstrate its success in improving student learning and achievement (Collins et al., 1991; Dennen & Burner, 2008; Wu et al., 2016).

The impetus for this study was the documented success of LbE in other educational contexts. LbE has proven to be an effective technique in higher education (Bartholomew, Mentzer, Jones, et al., 2022; Bartholomew, Zhang, et al., 2019) and in middle school (Bartholomew et al., 2018) for enhancing student learning. We, therefore, anticipated measurable gains in student learning and achievement at the high school level. However, a critical distinction between our study and prior research may be the scope of our measurement. In the higher education studies, for instance, learning improvements were measured on specific, targeted tasks. In contrast, our study attempted to detect improvements at a broader project level, using average design journal scores as the primary

metric. Therefore, a plausible explanation for non-significant results is that our approach masked more granular improvements (i.e., time management or the quality of entries in a decision matrix that teachers may have targeted with their LbE sessions). Students may have experienced gains on specific design activities, such as producing more creative ideas or more complex prototypes, but these nuanced changes were not captured by the overall project score or rubric criteria associated with the specific design activity.

Furthermore, a potential mismatch likely existed between the content of some LbE sessions and the criteria assessed by our rubric. Ideally, we would analyse the specific LbE sessions each instructor ran and relate those to performance gains on specific design criteria, but our data collection was unable to capture which sessions were run by which teachers during this design journal study. We discovered that instructors often refreshed older LbE sessions for new activities instead of creating new ones, which meant we could not systematically track the precise content or frequency of the sessions that were actually run using the teacher's history of sessions in RM Compare. Nonetheless, our broader engagement with the classrooms as part of a larger NSF project allowed us to observe instructors applying LbE to valuable skills like improving the quality of brainstorming or enhancing time management via Gantt charts. While these are important professional practices, they are not directly measured by EfA design journal rubric. This suggests that students could have been learning and improving in ways that our study was simply not designed to measure. We will explore the limitations of our instrument in greater detail in the subsequent section.

Limitations Associated with the Rubric Fit

A significant limitation of this study was the alignment between the general measurement instrument and the specific LbE treatment. The rubric was designed for teacher led classroom assessment, which we suspect would have been successful based on our use. However, as a research instrument, it proved to be a poor fit for the needs of this particular study, which was not evident until analysis was completed. The rubric design prioritized the completion of tasks (appropriate for classroom teacher assessment—its designed intent) over a detailed inspection of performance quality (needed for this research).

This difficulty in examining fine-grained levels of performance was manifest in several elements of the rubric design. The rubric had a 3-point scale (1 to 3), which we expanded to a 4 point scale (0 to 3). However, the instrument still likely lacked numerical granularity to capture certain improvements, based on the typical design performance of the student participants. For instance, under *Research and Investigation* (Criterion 2), the rubric evaluated if research had been conducted, but not the quality of the research or its impact on the design work. We speculate LbE may improve students' critical thinking which may emerge in ways that are demonstrated through more meaningful research as

opposed to the binary presence of research or not. Thus, while parts of the rubric valued completion, we hypothesize LbE might improve quality, not completion. This represents a significant limitation for our study, as it renders a crucial aspect of intellectual development—the increasing sophistication of student inquiry—largely invisible to the assessment.

Several aspects of classroom scaffolding may also have amplified the difficulties of using the rubric to evaluate performance within a research study. In several cases, teachers' typical classroom practices created an artificial ceiling when combined with the rubric focus on completion rather than quality. We hypothesize this was the case for *Stating the Design Challenge* (Criterion 1a).

In our analysis, we observed that students consistently earned a score of 2 by *restated [the problem statement] exactly as provided by the instructor*. To achieve a 3, the rubric required students to independently reframe the problem to explain the need for the project. Although the higher level does reflect increased sophistication with design documentation, if students were only instructed to perform the action that earned a score of 2 (i.e., restate exactly as provided), it would explain why students typically did not achieve the highest level. This same pattern could have occurred with the *Research and Investigate* criterion, where students may have precisely followed instructions (i.e. research exactly 5 questions) which corresponded only to a mid-level score on the rubric.

Conversely, other criteria were susceptible to a different kind of ceiling effect, where the requirements for the highest score were met with relative ease. For *Clarifying Constraints* (Criterion 1c) and *Generate Alternative Solutions* (Criterion 3), most students identified several design constraints (probably teacher provided) and had multiple ideas that differed from their final idea and therefore received the maximum score of 3. While this indicates strong performance, it also means the rubric could not differentiate between students who met the high standard and those who significantly surpassed it.

Limitations Associated with the Design Journals

This study is situated within a larger, five-year NSF-funded project investigating Learning by Evaluating. While the current analysis was designed to assess student learning based solely on the evidence available within engineering design journals, our understanding of the context is informed by our broader engagement with the participating classrooms. The journals, however, often failed to provide a comprehensive record of the students' design processes. This created a significant discrepancy between the activities we witnessed during our ongoing observational visits and how students' work was actually documented.

This issue of incomplete documentation was widespread. Of the nine instructors involved in the larger project for the academic years of 2023-24 and 2024-25, only two consistently required students to maintain their work in a single, coherent design journal. While these two teachers had the richest

journals, even amongst them, journals were often missing key entries of the design journey, contrary to the best practices outlined by Kelley (2011), which emphasize diligent, chronological recording of all design activities.

The evidence of this incomplete documentation was most apparent in the scoring for *Develop a Prototype* (Criterion 5). During our observational site visits—which were part of the larger grant's activities but not a formal data source for this particular study—we frequently saw students constructing both digital and physical prototypes. Yet, because this work was not consistently recorded in the paper based journals, many students did not receive a high design journal score for their prototyping work, due to a lack of documented evidence. Our direct observations allow us to surmise with confidence that most students did, in fact, complete the prototyping stage, but they failed to include the necessary evidence in their journals. Instead, they may have been evaluated by the teacher's observations or there may have been digital submissions to the school-wide LMS software that captured the process but were not entered into the design journal. Consequently, relying solely on the design journals, as dictated by this study's methodology, provided an incomplete and potentially misleading representation of student achievement.

Implications for TEE

Implications for Practitioners

The findings of this study offer several key implications for technology and engineering practitioners. Our analysis showed a significant improvement in students' overall design journal scores over time, affirming that valuable learning is occurring regardless of our LbE treatment. However, our findings also highlight opportunities to enhance this practice by addressing two key areas: (1) the need for improved, practice-based documentation strategies and (2) a fundamental tension between prescriptive instruction and the development of authentic engineering habits of mind.

Re-envisioning the Engineering Design Journal as a Practice-Based Tool

A central tenet of using engineering design journals is to make student reasoning visible, thereby enabling authentic assessment (Asunda & Hill, 2007; Kelley, 2011). Our finding that most instructors did not use journals this way suggests there is a significant gap between pedagogical theory and classroom reality. This gap presents an opportunity to consider documentation approaches that are practice-based. Such a practice-based approach might be a better reflection of classroom dynamics, where the work students complete is often digital, collaborative, and multimedia-rich. Rather than being a static repository, contemporary, practical journals could be a dynamic digital space where students embed videos of prototype tests, link to simulations, and collaborate on technical drawings.

The gap between design journals as authentic assessment and their practical use appears to be one of integration; when documentation is perceived as an onerous task separate from the *real* work of designing and building, students and teachers may be less likely to engage with it deeply (Paretti, 2008). Future work should therefore focus on making documentation a more authentically practice-based endeavour. A promising approach could be to co-develop new resources directly with instructors, ensuring that solutions are grounded in classroom realities. This collaborative work could include creating new practice-based implementation frameworks or exploration with digital platforms that better integrate documentation into the design process, framing it as a natural and valued part of the engineering workflow. With these blended modalities and platforms, transitioning the historically paper based design journal to a digital structure may expand the comprehensiveness and utility of engaging in design documentation.

On the other hand, absent such a platform, effectively evaluating student design documentation may require that information be combined from several sources. Our observations indicated that students were making sketches on paper and doing CAD work on their computers. Prototype testing was done in class but could have been documented with video or photographic evidence. Therefore, integration of student design documentation may require examining paper-based journals, computer and empirical testing, digital LMS submissions, and in person observation when presentations are employed for assessment.

Balancing Instructional Scaffolding with Authentic Engineering Habits of Mind

Beyond documentation, our analysis raises a fundamental question about how design is taught in secondary education. While the stated ideals of the field emphasize the cultivation of engineering habits of mind, such as systems thinking (Lucas & Hanson, 2016), our analysis revealed student work that was often highly uniform, implying that it was prescriptive. As examples, students were expected to restate the design problem exactly as provided by the instructor and many of the constraints and criteria were identical within classes. A prescriptive approach, while efficient, is in direct tension with the goal of fostering authentic problem-solving. This tension may point toward a pedagogical *sweet spot* where instructors provide structure by defining the boundaries of a problem space (e.g., specifying certain materials, software, or a target performance metric), yet leave the pathway to the solution genuinely open-ended. Such a strategy could provide necessary guidance while still entrusting students with intellectual agency.

A valuable direction for future research, therefore, would be to investigate learning progressions associated with secondary design education with specific attention to scaffolding novice designers sufficiently. For example, comparative studies could examine differences in student learning, creativity, and systems

thinking when taught in highly prescriptive environments versus more open-ended, yet constrained, ones. Furthermore, another line of inquiry could focus on developing resources or frameworks that help educators design effective learning experiences that balance necessary constraints with the freedom to innovate.

Implications for Researchers

Rather than concluding that Learning by Engineering (LbE) may be ineffective in measurably improving student learning in high school settings, we argue the primary implication of this study is methodological. We have aimed for transparency in our research process so that subsequent work can better navigate the complexities of measuring LbE's effects. Our findings suggest that for results to be clear, there must be a much tighter alignment between the specific goals of an LbE intervention and the constructs being measured. A review of available instruments to measure secondary introductory level design process documentation was conducted prior to this study and resulted in few options. Thus, future research could refine a valid and reliable research grade instrument for measuring design to fill this gap.

With a more rigorous instrument our study's next weakness was sample size. Future research should be situated in classrooms where design documentation is an expectation. While nine teachers participated in the larger study, and most teachers had what they called design journals, they typically expected students to use these as notebooks rather than design journals. Thus, upon close review, we discovered the design journal was more of a collection of lecture notes, including anything students were asked to write down in preparation for a test, draft research papers, or notes when a guest speaker was coming into the classroom. To complicate our limited teacher sample, we recommend future researchers work closely with the school community during the consent process as we struggled to secure parent consent. Few parents actively said no, but, rather, our struggle was simply getting a response.

Conclusion

This study sought to determine if Learning by Evaluating (LbE) could significantly improve student achievement in secondary school engineering design. Despite LbE's promising foundations, our primary finding was that the LbE intervention did not produce a statistically significant improvement in student design journal scores compared to standard classroom practice. We conclude that this outcome is likely not an indictment of LbE itself, but rather a reflection of the limitations of the measurement strategy used in this study. While the rubric used may be suitable for classroom assessment, it was general and focused on task completion over quality. Its inability to capture nuanced or qualitative growth may have masked student learning associated with our

treatment. Second, a mismatch between LbE activities and the assessment criteria also likely rendered genuine learning gains invisible to our analysis.

Therefore, the primary contribution of this work is a critical insight into the challenges of authentic assessment in K-12 engineering education. Our findings compel a shift in focus from merely implementing new teaching techniques to fundamentally rethinking how we measure complex learning. This points to two clear implications for practitioners: the need for better integrated, practice-based documentation that make student thinking truly visible, and a pedagogical move away from prescriptive instruction toward creating more open-ended, yet constrained learning experiences.

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Conflict of Interest Statement

The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval

This study was approved by the Purdue University IRB and administrators of participating school districts. Participating teachers, students and students' parents provided consent and assent as required by Purdue University IRB. All participants were informed about the study during the consent/assent process which included the intention to publish the study findings, ensuring no individuals could be recognized.

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Amidst the Abyss: An Update on Undergraduate Technology and Engineering Education Programs

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Abstract

The primary goal of this study was to develop a comprehensive list of active technology and engineering teacher preparation programs (TETPPs) in the United States by cross-referencing reports from Love and Maiseroulle (2021) with data from the National Center for Education Statistics (NCES). A secondary goal was to assess the current status of TETPPs through an examination of their enrollments and program structures based on a convenience sample of these programs indicating recent affiliation with the Technology and Engineering Education Collegiate Association (TEECA). Research findings indicated that only 50% of the TETPPs identified in the 2021 list (Love & Maiseroulle) were also identified through the NCES search as those preparing teachers in technology and engineering education (TEE). The other 50% of the programs were unique to each list respectively.

Findings regarding the current status of active TETPPs with recent TEECA affiliation indicated enrollment numbers for students pursuing licensure ranged significantly, from 7 to 135 depending on the institution. Findings also revealed that the structure among TETPPs with recent TEECA affiliation also varied significantly depending on the institution, which may hold implications for continued program success. These findings demonstrated that, while the number of TETPPs may be greater than previously thought, many programs with recent TEECA affiliation are struggling to maintain viability in terms of enrollment numbers, and that not enough is known about how TETPPs contribute to the overall supply of TEE teachers in the United States. A major recommendation is that researchers conduct a comprehensive, ongoing survey of supply and demand for TEE teachers in the United States that also addresses the demand for TEE teachers and the impact of alternative certification programs.

Keywords: Technology and Engineering Education, Teacher Preparation Programs, Teacher Shortage, TEE

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Introduction

A nationwide shortage of teachers in Technology and Engineering Education (TEE) has highlighted challenges for undergraduate technology and engineering teacher preparation programs (TETPPs) in meeting the demand for qualified technology and engineering educators (Moye, 2017; Ortiz, 2022; United States Department of Education, 2026). With TEE being a dynamic field with continual evolutions, a systems thinking framework was used to approach this research to evaluate how these evolutions have led to changes in TETPPs. Despite efforts by faculty and leaders to align with educational and industry demands, TETPPs have struggled to survive and succeed in the burgeoning world of academic programs. Understanding the number, enrollment and structure of TETPPs is a vital first step toward identifying successful programs and, ultimately, for addressing these challenges and increasing enrollment and graduation rates (Love & Maiseroulle, 2021; Moye, 2017). By identifying the structure and practices of surviving programs, stakeholders can develop targeted strategies to enhance recruitment, improve their program, and support student experiences, all of which are essential to alleviating the teacher shortage (Moye, et al., 2020).

Previous efforts to list TETPPs (Love & Maiseroulle, 2021; Volk, 2019) have resulted in incomplete data or other discrepancies that were noted by the authors when reviewing literature as a part of other research, thus providing the rationale for this study. The purpose of this study was to better understand factors that may affect the ability of students seeking TEE teacher certification to enroll in and complete TEE teacher certification programs including the number of available programs, and indicators of the health of these programs such as enrollment and structure. Toward this purpose, the primary goal of this study was to develop a more comprehensive list of active TETPPs by cross-referencing findings reported by Love & Maiseroulle (2021) with active programs listed in the National Center for Education Statistics (NCES) Classification of Instructional Programs (CIP) database. A secondary goal was to examine the enrollment and structure of a convenience sample of current TETPPs with recent affiliation (within the past 10 years) with the Technology and Engineering Education Collegiate Association (TEECA). Despite the shared goal of preparing TEE teachers, there are vast structural differences amongst these teacher preparation programs (Love and Maiseroulle, 2021). These structural differences may have impacts on enrollment and other potential indicators of program health, thus prompting us to further investigate the enrollment and structure of these programs.

Literature Review

The TEE Identity Crisis

Technology and Engineering Education has transformed multiple times to maintain relevance (Reed & LaPorte, 2015; Wicklein, 2006), leading to an

identity crisis (de la Paz, 2017). Over the last 40 years, the national organization for technology and engineering educators evolved from the American Industrial Arts Association (AIAA) to the International Technology Education Association (ITEA), followed by the International Technology and Engineering Educators Association (ITEEA), reflecting the shift from industrialization to a technological society (Litowitz, 2008). While the intent of the change may have been generally understood or accepted, critics argued that these changes lacked coordination and did not produce fundamental reform (Bybee & Loucks-Hoursley, 2000). It is within this environment that the national Standards for Technological Literacy (STLs) were developed, which began to formalize engineering as a part of technology education in an effort to unify, guide, and direct TEE (Hook, 2001; International Technology and Engineering Educators Association [ITEEA], 2000/2002/2007). However, technology education continued to grow and evolve.

By the year 2000, engineering was gaining popularity in education (Litowitz, 2008; Reed & LaPorte, 2015). Across the nation, states were adopting engineering standards for their curriculum (Carr, et al., 2013; Moore et al., 2015). Carr, et al. specifically found that 41 states had standards related to engineering, including 15 states that had borrowed language from the STL--but there were no nationally accepted standards for the expected skills or knowledge in this instruction (Katehi, et al., 2009). It should be noted that within the United States, authority to determine educational standards rests with individual states; thus, national acceptance here refers to widespread adoption by individual states. Standards developed by one state or a consortium of states, or a professional association (along with any combination of these) may be adopted by other states, with or without modification. In response, groups such as the National Research Council (NRC, 2009), supported the development of standards for engineering education at the K-12 level. While this was received with general agreement, some felt that another name change for the profession was necessary to avoid confusion as to the true nature of technology education (Starkweather, 2008). Starkweather (2011) noted that "the profession's position within the entire education community was thought to be stronger if both technology and engineering content were addressed by our profession and association" (Shaping the Brand, para. 2). In 2010, ITEA added "Engineering" to its name, becoming the International Technology & Engineering Educators Association (ITEEA) (Strimel, et al., 2016). Shortly thereafter, the Next Generation Science Standards (NGSS) were updated to incorporate engineering principles within science education (NGSS Lead States, 2013), highlighting the need for engineering design principles to be integrated in other core subjects (Moore, et al., 2015). Prior to this, Moore, et al. had found that only 12 states had explicitly incorporated engineering into their science standards. In contrast, currently 20 states and the District of Columbia have formally adopted NGSS science standards, while an additional 29 states have used NGSS as the basis for their

science standards (National Science Teaching Association, 2026) In 2020, ITEEA released the updated Standards for Technological and Engineering Literacy, formalizing the addition of engineering as part of the content taught within TEE by a national professional association. Yet, it remains to be determined the extent to which these changes have or will be adopted by individual states within their standards.

With the official adoption of engineering as part of the discipline, some argued that instead of clarification and direction, the changes have precipitated yet another wave of the identity crisis (de la Paz, 2016, p. 8). Rigler (2016) argued that to set TEE apart, TETPPs need to recognize that the core of the profession is still Industrial Arts. He asserted that the changes and additions of technology and engineering are not unwelcome, but that the profession and organization must not erase industrial arts classes. Others argued that the profession must remain focused on technological literacy and transferable skills (Love, 2016), while yet others argued that the focus should be integrative STEM (I-STEM) education to intentionally integrate each STEM element through TEE content and pedagogy (Sanders, 2008; Wells & Ernst, 2012/2015). However, the integration of engineering with technology education curriculum was perceived to show promise with its ability to provide additional opportunities to increase technological literacy and introduce students to more future career options (NRC, 2009).

For TEE teachers to effectively teach current secondary TEE courses, they must be prepared with content and pedagogical content knowledge relevant to their discipline (Wood, et al., 2024). As Moore et al. (2014) noted, "engineering education at the K-12 level should emphasize this interdisciplinary nature, including the integration of [science, math, and engineering]" (p. 5). With the current emphasis on engineering, this should include a robust knowledge of engineering principles and pedagogical content knowledge for teaching engineering. However, TETPPs frequently require no specific coursework in engineering, instead allowing content-area training to come from coursework that aligns with traditional industrial arts curriculum, with courses ranging from energy and power technology to graphic design (Litowitz, 2014). This gap (along with other factors) has helped open the door to competition from other teacher training programs such as Project Lead the Way (PLTW), which provides professional development and training to prepare teachers from any content background to teach engineering at the secondary level, including those with no formal training or background in STEM. Volk (2019) argued that the development of PLTW's curriculum helped to provide TEE teachers resources and education while also decreasing the need for TETPPs. These alternative training and licensure programs are not the only thing complicating the perception of traditional teacher preparation programs.

Technology and Engineering Education within Career and Technical Education

An additional complication amongst TETPPs is overlap with Career and Technical Education (CTE), which encompasses elective courses (i.e., agricultural education, sewing, foods, computer science) and/or STEM (Science, Technology, Engineering, and Math) curriculum. Most TEE programs at the secondary level are funded in part through federal technical education allocations under the Perkins Act, or state and local funding designated for CTE in America, which emphasizes workforce development and career preparation. In many states, TEE does not function as a discipline separate from CTE but rather fits under the CTE umbrella in terms of funding, administration, and perception within the education system and by the public. In states that have adopted the CTE Pathways model, TEE has been functionally eliminated as a distinct discipline within CTE, as secondary courses previously fitting under this designation are now split between various narrow career pathways which are in some cases administered by multiple pathway specialists who oversee course designations, standards development, teacher endorsements, etc. Thus, the success of TEE programs at the secondary level, as well as TETPPs by extension, is inseparable from trends taking place within CTE.

Previously, fluctuations in financial support from the government at both the state and local level have coincided with a decline in the number of CTE classes offered nationwide (U.S., 2006). Camp and Heath-Camp (2007) argued that the decline in CTE secondary program enrollment was caused, in part, by the implementation of high-stakes testing, No Child Left Behind Act of 2001 (NCLB), which implemented regular standardized testing to evaluate math and reading yearly progress, along with funding patterns in Perkins legislation. It is possible that a decrease in TEE program enrollment may have created a negative feedback loop, where a lack of qualified teachers has led to secondary TEE program closures and a reduced need for TEE teachers, potentially contributing to losses of TETPPs following NCLB (Brown, 2012). More recently, however, Irwin, et al. (2023) argue that federal data has shown that 85% of students participate in CTE courses during their secondary education. Smith & Dougherty (2024) argue that this increased student involvement has increased federal and state-level funding to support TEE course enrollment, potentially increasing the demand for TEE teachers. Concern over unfilled technical positions within industry and student interest has led to a call for increased access to TEE courses (Palaniappan, 2020; USDOE, 2000). How these trends have specifically impacted TETPPs remains unclear. However, without strong TETPPs, student access will continue to be limited as the shortage of qualified teachers increases (Deever, et al., 2020) and declining enrollment in TETPPs (Fletcher & Gordon, 2017; Moye, 2009; Volk, 1997) continues to deepen.

Technology & Engineering Teacher Preparation Programs

The past 45 years have shown a decrease in TEE teacher preparation programs across the nation (Love, 2016; Moye, 2009). In 2015, ITEEA reported 43 existing TETPPs, showing a large decrease in the span of eight years from a reported 72 programs in 2007 (Warner, et al., 2007). Despite efforts to ensure the future of TETPPs, serious questions persist regarding the stability and strength (i.e., enrollment numbers) of these programs, and how to support future sustainability and growth (Love & Love, 2022).

One major issue surrounding the effort to determine the strength of TETPPs is ambiguity as to what constitutes a TETPP. As discussed in previous sections, the profession continues to struggle with a seemingly intractable identity crisis, with mismatches between the name of the profession, content delivered at the secondary level, overlap with other CTE disciplines, and misalignment with TETPPs. It should come as no surprise that previous efforts to catalog and assess the health of TETPPs have delivered conflicting results (Love & Maiseroulle, 2021; Volk 2019). Volk (2019) prophesied the impending doom of "traditional" TETPPs, noting the existence of only 32 such programs. However, only three years later Love and Maiseroulle (2022) argued that TETPPs have not generally disappeared (notwithstanding several program closures they noted in recent years), but have instead transformed to offer TEE teacher licensure through certificates, emphases, and graduate degrees that not only certify educators of secondary education, but some teacher preparations extend to licensing educators for the Pre-primary education space. The Love & Maiseroulle 2021 analysis of Technology and Engineering Related programs in the United States identified a total of 74 teacher preparation programs, three of which were found to be discontinued. This brought the list of *active* teacher preparation programs offering certification to teach TEE-related courses to 71, which is more than double Volk's count. The disagreement between these two studies seems to stem from different approaches to what constitutes a TETPP. In their 2022 publication, Love & Maiseroulle presented a more inclusive approach by including any teacher preparation program certifying teachers in Integrative STEM Education (I-STEM ED), those that existed as emphases, certification programs, and graduate programs, whether associated with ITEEA or not. Volk, on the other hand, seems to have considered mainly four-year undergraduate degree programs that have traditionally been associated with ITEEA.

Because of these conflicting results, which seem to stem from deeper differences in philosophy regarding the name and nature of the profession, the shifting content demands at the secondary level, and overlap with CTE, it remains difficult to conclude what trends are actually occurring with respect to TETPPs, or even how many exist. While the present study does not attempt to resolve the deeper philosophical issues, the purpose of this study was to develop a more comprehensive list of TETPPs, and secondarily to take initial steps to assess the enrollment and structure of existing TETPPs.

Research Objectives

Given the purpose and goals of this study, the following research objectives were developed:

1. Identify existing teacher preparation programs that prepare students for certification to teach technology and engineering education.
2. Identify the enrollment and structure of technology and engineering teacher preparation programs that have been affiliated with TEECA within the past 10 years.

Method

This study engaged a systems thinking conceptual framework evaluating TETPPs as a dynamic system with interconnected components instead of isolated structure. From the evolutions in TEE as well as education, systems thinking evaluates the structure TETPPs from its interconnected parts (i.e., program name or a focus on industry versus education). To better understand the current landscape of TETPPs, this exploratory study employed a combination of data collected from program representatives together with content analysis of primary sources. This dual approach allowed for a thorough investigation of program existence and structure in instances of non-response. The method guiding these processes is outlined below, organized by the study's research objectives.

Research Objective 1: Identifying Teacher Preparation Programs

Due to the debate surrounding the different conceptions of what constitutes a 'true' TEE teacher preparation program (de la Paz, 2016), our process for identifying teacher preparation programs in TEE was two-pronged.

First, we sought to identify the most recent existing lists or directories of TETPPs. Several such lists have been published over the years, including recent lists by Volk (2019), and Love & Maiseroulle (2021). In addition to these lists, the ITEEA Council on Technology & Engineering Teacher Education (CTETE) has historically published program directories on a periodic basis. However, in our attempts to locate the most recent directory, it was discovered that the last directory was published prior to the COVID-19 pandemic, and that in a website transition the access to these directories has been lost. This left only the lists by Volk (which drew from the 2017 CTETE directory) and Love & Maiseroulle. While only two years more recent than Volk's 2019 list, the list produced by Love & Maiseroulle in 2021 also offered the advantage of a wider scope which included the 2019 CTETE directory as well as additional programs identified through a content analysis of university teacher preparation programs related to TEE. This differs from Volk's list which was confined to programs that had been traditionally associated with ITEEA/CTETE via the directory. For this reason, we selected the 2021 Love & Maiseroulle's data file as the most recent

and comprehensive list, which identified a total of 74 teacher preparation programs. It is important to note that of the 74 listed in the data file, three were noted as having been discontinued, which brought the list to 71 *active* teacher preparation programs offering certification. However, when publishing their findings in 2022, they indicated that additional content analyses of websites revealed a total of 70 programs across 35 states (p. 11, Table 2). Their 2022 publication did not identify which of the programs listed in the 2021 data file had been excluded.

The second prong consisted of conducting a search using the National Center for Education Statistics (NCES) College Navigator tool, which utilizes the Classification of Instructional Programs (CIP) code to identify post-secondary programs in specific areas. Our search used the CIP code for Technology Teacher Education/Industrial Arts Teacher Education. The results from this CIP code search were then cross-referenced with the list of Technology Teacher Education programs identified by Love and Maiseroulle (2021) to generate a comprehensive list of potential teacher preparation programs, including any programs newly identified through the NCES database. Following this step, an institutional website/catalog search was conducted for each newly identified program to determine whether it was active and led to teacher licensure.

In the current study, a technology and engineering teacher preparation program was defined the same as in Love & Maiseroulle (2022), that is, in summary, a university program offering teacher certification with a curricular focus on technology and engineering literacy and/or alignment with the Standards for Technological and Engineering Literacy (ITEEA, 2020). An *active* TETPP in this study was defined as one which was listed on the respective university departmental website and/or catalog and appeared to be accepting students.

Research Objective 2: Assessing the Enrollment and Structure of TEECA-Affiliated Programs

As a starting point to assess the health of TETPPs, we chose to investigate the enrollment and structure of programs with current or recent membership in ITEEA's pre-professional program, TEECA. Participation in TEECA signifies that the program is providing their students opportunities to network on a national level along with institutional support. We defined recent affiliation as within the 10 years prior to the start of this study (between 2014-2024). While there are clearly more TETPPs available than only those with recent TEECA affiliation, we viewed this as a convenient starting point that should be expanded in future studies.

To gain a better understanding of TEE programs across the United States, program faculty from the 20 programs having been affiliated with TEECA since 2012 were contacted via the TEECA advisor email listserv and asked to explain

the structure and provide enrollment numbers for their teacher preparation program. The request included an invitation for elaboration if they felt that it was necessary or helpful. The specific questions for this study covered the following information:

- The official name of their program
- Whether it was solely licensure or if it was a technical degree with teacher licensure as an option.
- Enrollment numbers: If they had teacher licensure as an option, they were asked to provide enrollment numbers for licensure vs industry path

Faculty members from 13 of the 20 programs responded. Enrollment data were reliant on faculty members having accurate and up to date information for each of their institutions.

Findings

Research Objective 1: Identifying Active TETPPs

The NCES College Navigator search identified 74 universities that have programs listed under the Technology Teacher Education/Industrial Arts Teacher Education CIP code. Based on their 2021 analyses of TETPPs as identified through the 2019 CTETE directory and content analysis of related university teacher preparation program websites, the 2022 publication by Love and Maiseroulle presented an examination of 70 programs from across 35 states. It should be reiterated that Love and Maiseroulle took a broader view of what programs should be considered, including any program which offered TEE-related teacher certification, regardless of program structure, name, and/or affiliation with ITEEA. Furthermore, they noted that several programs they found through these resources had been discontinued. Cross-referencing the NCES and Love and Maiseroulle (2021) data (Table 1) resulted in a combined list of 111 teacher preparation programs related to technology and engineering education. Of these 111 programs, 37 were common to both lists, while the Love & Maiseroulle and NCES lists each had 37 unique programs respectively.

Table 1
Cross-reference of Love and Maiseroulle's (2021) and NCES' comprehensive list of programs

	Educational Institution	Love & Maiseroulle	NCES
1	Appalachian State University	X	
2	Augusta University	X	
3	Ball State University	X	X
4	Bemidji State University		X
5	Berea College	X	X
6	Black Hills State University*	X	X
7	Boise State University		X

8	Brigham Young University	X	
9	California State Polytechnic University-Humboldt		X
10	California State University, Los Angeles	X	X
11	California University of PA	X	
12	Casper College (2+2 with Valley City State)	X	X
13	Central Connecticut State University	X	X
14	Central New Mexico Community College		X
15	Central Washington University	X	
16	Cerritos College		X
17	Chadron State College		X
18	Chicago State University		X
19	Clemson University		X
20	CUNY City College		X
21	Colorado State University	X	
22	Delta College		X
23	Dickinson State University		X
24	East Tennessee State	X	
25	Eastern Illinois University	X	
26	Eastern Kentucky University	X	X
27	Eastern Michigan University	X	X
28	El Camino Community College District		X
29	Fitchburg State University	X	X
30	Florida A&M University	X	
31	Fort Hays State University	X	X
32	Fox Valley Technical College		X
33	Fresno City College		X
34	Fullerton College		X
35	Hofstra University	X	X
36	Illinois State University	X	X
37	Indian Hills Community College		X
38	Indiana State University	X	X
39	Jackson State University	X	X
40	Kansas State University, Polytechnic Campus *	X	
41	Lakeland University		X
42	Lebanon Valley College	X	
43	Lincoln University		X
44	Loyola University Chicago		X
45	Loyola University Maryland		X
46	Marian University		X
47	McDaniel College	X	

48	Millersville University of PA	X	
49	Montana State University	X	
50	Morehead State University	X	
51	Murray State University	X	
52	New Jersey Institute of Technology	X	
53	New York City College of Technology	X	
54	North Carolina A&T University	X	
55	North Carolina State University	X	X
56	Northern Michigan University	X	X
57	Ohio Northern University	X	X
58	Old Dominion University	X	X
59	Pennsylvania Western University		X
60	Pittsburg State University	X	X
61	Purdue University	X	X
62	Rhode Island College	X	X
63	Rider University		X
64	Saint Cloud State University		X
65	San Francisco State University		X
66	Savannah State University	X	X
67	South Carolina State University	X	X
68	St. Catherine University	X	
69	St. Cloud State University	X	
70	SUNY Buffalo	X	
71	SUNY Oswego	X	X
72	Texas A&M	X	
73	The College of New Jersey	X	X
74	The Ohio State University	X	
75	Tufts University	X	
76	University of Arkansas	X	
77	University of Central Missouri	X	
78	University of Georgia	X	
79	University of Idaho	X	X
80	University of Maine		X
81	University of Maryland Baltimore County	X	
82	University of Maryland Eastern Shore	X	X
83	University of Maryland-College Park		X
84	University of Nebraska-Lincoln	X	
85	University of Nebraska-Omaha	X	
86	University of New Mexico-Main Campus		X
87	University of Northern Iowa	X	X
88	University of Puerto Rico-Carolina		X
89	University of Southern Maine		X
90	University of St. Thomas	X	

91	University of Texas El Paso	X	
92	University of Washington-Seattle Campus		X
93	University of Wisconsin, Oshkosh	X	
94	University of Wisconsin, Parkside *	X	
95	University of Wisconsin, Platteville	X	X
96	University of Wisconsin, Stout	X	X
97	University of Wyoming	X	X
98	Upper Iowa University	X	
99	Utah State University	X	X
100	Valdosta State University		X
101	Valley City State University	X	X
102	Vincennes University		X
103	Virginia Tech	X	
104	Viterbo University	X	X
105	Wayne State College	X	X
106	West Chester University of Pennsylvania		X
107	Western Michigan University	X	X
108	Western Washington University		X
109	Westfield State University		X
110	Widener University		X
111	William Penn University	X	X

*Love and Maiseroulle (2021) noted that these programs have been discontinued

While this cross-referenced list of TEE-related teacher preparation programs casts the widest net to date, it remained unclear which of these programs are active and what kind of certification (if any) they provided (e.g., secondary education, elementary education, STEM endorsement, etc.).

Programs Identified Through NCES Database

Of the 111 TEE-related teacher preparation programs initially identified (Table 1), 71 had already been identified and catalogued by Love & Maiseroulle (2020). The Love & Maiseroulle 2021 data file included information such as degree type, whether programs led to teaching credentials, etc. Utilizing the NCES database, an additional 37 programs were identified that did not appear on Love & Maiseroulle's 2021 list. As noted earlier, the NCES database only provided the name of the institution associated with the CIP code, but did not provide any information about whether these programs were active, whether they led to teacher licensure, etc. To alleviate this gap, a search was conducted of the web site for each institution to identify basic information about each of these 37 programs, including whether the program was active, the name of the program, and whether it led to teacher certification in TEE (elementary and/or secondary). The web search included listings of degrees/majors and certificates

available at each respective institution, as well as searches of related majors (e.g., secondary education, industry-focused technology programs, etc.) that might include TEE as a concentration/emphasis option rather than as a standalone degree program. For programs found to exist and be active, website and catalog searches were conducted to determine whether they offered teacher certification in TEE. Table 2 summarizes the results of this search, which for the sake of brevity, only includes active programs.

Table 2

Information on active programs newly identified through search of NCES database

University	Program Name	Licensure	Additional Notes
California State Polytechnic University-Humboldt	Secondary Education – Industrial Technology	Secondary	They can apply for a single subject credential.
Cerritos College	Career Technical Education		No information is provided on the program – it is unclear on its status, licensure, or requirements from a basic web search
Chadron State College	Career and Technical Education Supplemental Endorsement		This is an endorsement focused on teaching Work-Based Learning for grades 9-12 to be added onto secondary licensure in a different content area
Chicago State University	Career and Technical Education – Industrial Technology Education	Secondary	The degree has a concentration in Communication, Energy Utilization, Production, and Transportation
CUNY City College	Technology Teacher Education	Secondary	

Dickinson State University	Technology Education		This is a collaborative degree with Valley City State University who provides all of the content coursework
Fox Valley Technical College	Career and Technical Education Instruction		This is an Associate's Degree
North Carolina A&T University	Technology Education		Only available as a Master of Arts in Teaching
Lakeland University	Technology Education	K-12	
Pennsylvania Western University	Secondary Education – Technology Education	Secondary	Formerly California University of Pennsylvania
St. Cloud State University	Technology Education	Secondary	A Master of Science degrees is also available
University of Southern Maine	Self-Designed STEM Major – Elementary Education	Elementary	No longer accepting students
Vincennes University	Technology – Career/Technical Education Baccalaureate Concentration	Secondary	This is a 2+2 program with an Associate's degree in Education with a Technology concentration.
Westfield State University	Vocational Technical Education	None	Focus is on the trades. Degree not required for licensure in these areas in MA.

Note. Only programs exclusively listed in the NCES database that were currently active were included in this table. All programs are undergraduate baccalaureate programs unless otherwise noted.

Of the 37 additional programs identified through a search of the NCES database, only 14 could be located by searching the respective institution websites/catalogs as described above. One of the 14 programs (University of Southern Maine) noted that students were no longer being accepted. Programs listed in only the NCES database that could not be located through the web search, along with any related information that was located, can be found in Table 3.

Table 3

Programs identified through a search of the NCES database having no internet presence

University	Additional Notes
Bemidji State University	They have an Engineering Technology degree but does not show any path to teaching licensure currently offered.
Boise State University	They have Master of Educational Technology and Doctor of Education in Educational Technology degrees that do not result in licensure but require students to have an appropriate education background. It has the goal to prepare instructional designers, UX designers, etc.
Central New Mexico Community College	Offers an Alternate Teacher Licensure program that can be added to any Bachelor's degree.
Clemson University	They have a Work-Based Learning/CTE endorsement, but it is only available for Agricultural Education
Fresno City College	They have an Applied Technology Division that offers CTE programs, but it is a technical certification that does not include TEE licensure
Loyola University Maryland	They have a M.Ed. in Learning Design and Technology, which is a focus on instructional technology
Marian University	They have a Master's in Education Technology

Note: No information was found for a program at Delta College, El Camino Community College District, Fullerton College, Lincoln University, Loyola University Chicago, Rider University, San Francisco State University, University of Maine, University of Maryland-College Park, University of New Mexico-Main Campus, University of Puerto Rico, University of Washington, Valdosta State University, West Chester University of Pennsylvania, Western Washington University, or Widener University.

Research Objective1 focused on the identification of existing TETPPs through the cross-referencing of existing approaches to identifying these programs. In doing so, we sought to cast the widest possible net by including those programs identified by Love & Maiseroulle (2021) as well as programs identified through a search of the NCES database. Of the 37 additional programs identified within the NCES database, 13 were found to be actively recruiting and preparing TEE teachers. One additional program was active but was not accepting students and was therefore determined to be in the process of closure. Combining the 13 active programs found in the NCES data with that of the 71 active programs included in the 2021 Love & Maiseroulle data file, brings the total number of *currently active* TETPPs to 84.

Research Objective 2: Enrollment and Structure of TEECA-Affiliated Programs

Research Objective 2 focused on ascertaining the status of TETPPs, specifically with respect to programs recently affiliated with TEECA. Of the programs included in either list, 20 have been affiliated with TEECA between 2014 and 2024. Findings from data collected through requests sent via email to faculty members of TEECA-affiliated teacher preparation programs revealed differences in program titles, enrollment, and structure. Table 4 presents a summary of the data collected from program faculty, including program name/description, enrollment (including those seeking licensure), and additional contextual information that was provided by faculty from some programs. The reported enrollment numbers ranged from 7 to 175 students (M = 61.6 students, SD = 56.9). However, for students pursuing licensure, the range was 7 to 135 (M = 37.0 students, SD = 37.4 (Table 4). The highest enrollment was reported by SUNY-Oswego, with 175 students, 135 of whom were pursuing teaching licensure. Two programs reported an enrollment of seven students, all of whom are seeking teaching licensure. The largest discrepancy between total enrollment and those pursuing licensure was at Fort Hays State University (FHSU), which had 170 enrolled students with only 10 seeking licensure. Out of the 13 programs that responded, six had enrollments exceeding 50 students, and of those, three had 50 or more students pursuing education licensure. Four programs reported enrollments of 100 students or more.

Table 4

Summary of program information collected via email request from faculty in TEECA-affiliated programs

University	Program Name	Enrollment (seeking licensure)	Additional Program Notes
Brigham Young University (BYU)	Technology and Engineering Education (prior to 2020) Technology and Engineering Studies (2020 - present)	75(29)	TEE was teacher licensure only. TES offers licensure as an emphasis alongside an technical-track emphasis.
The College of New Jersey (TCNJ)	Held in the Department of Integrative STEM (iSTEM) under two majors 1. Technology and Engineering Education 2. iSTEM	25(25) TEE 75(75) iSTEM	TEE is a degree to teach in a secondary classroom. iSTEM is a joint major between the Elementary Education and Engineering. Pre-service teachers enrolled in iSTEM can pursue a technology specialization, which certifies teachers to teach technology in K-12
Fort Hays State University (FHSU)	Technology Studies	170(10)	Technology Education is an emphasis within an technical-focused program that offers teacher licensure
Illinois State University (ISU)	Technology and Engineering Education	32(32)	None provided

Millersville University (Millersville)	Technology and Engineering Education	60(60)	Offers teacher technology education licensure for Pre-K-12. TEE is part of the required science curriculum in the state. Vocational education falls under a separate certification
North Carolina State University (NC State)	Technology, Engineering, and Design Education (Major and Minor)	101(27)	The department offers two different technical-tracks The numbers reported for Technology, Engineering, and Design Education combine those enrolled in both the major and minor.
Ohio Northern University (ONU)	Technology Education	7(7)	Each student is trained for teacher licensure, but can opt out of student teaching which prevents them from receiving a teaching license.
Old Dominion University (ODU)	Career and Technical Education with an emphasis in Technology Education	7(7)	None provided
Pennsylvania Western University (PennWest)	Technology Education (prior to 2022) Secondary Education with an emphasis in Technology Education (2022 - present)	19(19)	The change was due to drops in enrollment and was absorbed by Secondary Education
Pittsburg State University (Pitt State)	Career and Technical Education with an emphasis in TEE	20(20)	None provided

Purdue University*	Engineering and Technology Teacher Education	19(19)	None provided
The State University of New York – Oswego (SUNY-Oswego)	Technology Education	175(135)	Also offers an industry track titled Technology Management.
Utah State University (USU)	Technology and Engineering Education (Major and minor)	16(16)	As of 2023-2024, USU started a stackable program for students with certifications from technical colleges to earn teacher licensure. A Masters' degree in TEE is also available but does not include licensure.

*Since the initial data collection, faculty have noted that they are no longer accepting new students and will be closing their program

In addition to overall enrollment, some programs provided their recent graduation rates of licensed teachers (Table 5). Brigham Young University (BYU) also provided the graduation rates from the last two years during which time it was a solely teacher licensure program, as well as graduation rates after the transition to an industrial track program with teacher licensure as an emphasis. The report from Millersville University also specified that graduating with licensure did not mean students chose to become teachers.

Table 5

Graduation reports from TEECA-affiliated teacher preparation programs

School Name	Graduation reports
BYU	Technology and Engineering Education (licensure program) 2018 = 18 graduates (all teaching) 2019 = 12 graduates (all teaching) Start of Technology and Engineering Studies (licensure emphasis) 2020 = 17 graduates (6 Teaching and 11 Technical) 2021 = 25 graduates (10 teaching, 15 Technical) 2022 = 21 graduates (7 teaching, 14 Technical) 2023 = 15 graduates (6 Teaching and 9 Technical)
Millersville	2022-2023 = 13 graduates (11 intended to teach)
NC State	About 7 teachers/year
SUNY-Oswego	25-30/year
USU	2022-2023 = 5 graduates (all teaching)

Our findings revealed a wide variety of program structure characteristics, such as name, type of program, and type of licensure, as well as program health as measured by enrollment across TETPPs affiliated with TEECA.

Discussion and Recommendations for Future Research

The purpose of this study was to gain a better understanding of contextual factors in the field of technology and engineering education that may impact TEE students seeking teacher certification in TEE. For this study, these factors include the number of available programs as well as the enrollment and structure of existing programs, which may be construed as indicators of program health. The research objectives were developed to address the goals of developing a more comprehensive list of existing TETPPs, inclusive of information regarding program enrollment and structure.

Our study identified an initial list of 108 teacher preparation programs that prepare students for teacher certification in TEE-related subject areas. This list was generated by cross-referencing the work of Love & Maiseroulle (2021, 2022) with programs reporting themselves to the National Center for Education Statistics as Technology Teacher Education/Industrial Arts Teacher Education programs via their CIP code. Of these 108 programs, 71 were previously identified and catalogued by Love & Maiseroulle (2021). An additional 37 programs were identified exclusively in the NCES database; i.e., not found in

Love & Maiseroulle's list. However, from the NCES database it is unclear whether any of the programs actually existed or were active, and, if so, whether they still provided teacher licensure in TEE subject areas. To address the issue, website searches of these 37 institutions were conducted to determine the status of these programs. Searches revealed a total of 13 programs actively preparing and recruiting TETPPs. Combining these 13 with the 71 already catalogued by Love & Maiseroulle, our research indicates that a total of 84 active TETPPs currently exist in the United States.

Status of True TEE Programs

An obvious caveat to this list of 84 programs is that we have not answered the question: What is a *true* technology and engineering education teacher preparation program. Volk (2019) contended that only about 32 programs existed at the time of his article, while Love & Maiseroulle included 71 programs – more than double Volk's estimate. Our list now includes 84 possible TETPPs. The actual number of programs truly preparing technology and engineering teachers to a large degree depends on how one defines a technology and engineering teacher preparation program. A more traditionalist approach, for example, which might restrict inclusion to only those that have historically been associated with ITEEA will lead to a smaller list, while a more inclusive approach that includes teacher preparation programs for STEM educators will lead to a larger list.

One might also argue that Career and Technical Education (CTE) is epistemologically at odds with TEE, and that programs with a focus on preparing vocational education teachers ought to be excluded. A full discussion of the strengths and weaknesses of any of these or other approaches is outside the scope of this investigation; however, we note that this discussion is still relevant, and even crucial to the future of the profession. Without a clear identity and direction for the future, professional organizations and leaders within the TEE profession cannot effectively articulate the importance of technology and engineering to policymakers and other stakeholders on a local, state, or national level. A *big tent* approach is alluring in that it may result in an increase in the number of educators and other professionals who associate themselves with the TEE profession. Historically, this seems to have become a possible strategy to growing the profession as Industrial Arts led to Technology Education, which became Technology and Engineering Education, and has now grown to include Integrative STEM Education. However, a hidden danger may exist in being everything to everyone. If clear boundaries are not drawn as to what does and does not constitute technology and engineering education (and, by extension, what does and does not constitute a TETPP), there is a risk that TEE may lose its identity as a distinct discipline. While we initially set out to build on the work of Volk (2019) and Love & Maiseroulle (2021, 2022) to determine the number of TETPPs still in existence, the results suggest further research is needed to

address the fundamental question: What is technology and engineering education in the 21st century?

Assessing the Health of Teacher Preparation Programs

We also collected information from a convenience sample of 13 faculty members (Table 4) in teacher preparation programs that were affiliated with TEECA within the past 10 years. Our findings from these data indicate wide variability in program structure, with some teacher preparation programs existing as standalone programs focused exclusively on teacher education, and others consisting of a teaching emphasis within or alongside industry-focused degree programs. In addition, some programs included other teaching certification tracks such as elementary STEM or other CTE teacher certifications.

Our findings also indicate wide variability in enrollment, with some programs enrolling fewer than 10 students and others with more than 100 students, and similarly disparate trends for graduation numbers at the time our data were collected. The two programs that reported the highest enrollment rates did have a technical track. However, Fort Hays State University (FHSU) showed that the majority of their students were on the technical track whereas SUNY-Oswego showed the majority of their students pursuing teaching licensure. While drawing conclusions about TETPPs generally from this convenience sample is not advisable, the findings do provide an illustration of the variability across TETPPs, which makes cataloguing and assessing the health of these programs a challenge. While we have tacitly assumed in this study that enrollment is an important indicator of the strength (health) of TETPPs, our findings uncovered other possible factors that could contribute to strong TETPPs.

One of these possible indicators that emerged from our findings was the composition of the home administrative unit of the TETPP. When we initially sought enrollment information from TETPP faculty, several responded asking whether they should include total enrollment or just those seeking teaching licensure. Through this we learned that several of the TETPPs we contacted were housed in administrative units alongside industry-focused programs, or that their entire teacher-education program was an emphasis or concentration within a program that prepared both industry professionals and teachers. This included multiple programs with relatively robust enrollment numbers. Other faculty indicated that their programs were part of administrative units that were focused on CTE teacher-preparation, and included programs such as Agricultural Education, and Family & Consumer Science Education. Still others were in units focused on general teacher education, such as Mathematics, Science, and Language Arts.

Some research has suggested that TEE students became aware of TEE through an initial interest in technical subjects (the content) rather than an initial

interest in teaching (Furse, et al., 2025; Love & Love, 2022; Yoshikawa-Ruesch, 2024). If this holds true, TETPPs that are housed alongside industry-focused programs may have advantages when it comes to recruiting students out of industry-track programs into teaching. These programs could potentially also benefit from access to more robust technical coursework and a broader availability of faculty expertise to teach the technical content associated with TEE. While our data were not sufficient to draw any of these conclusions, a future study could categorize a broad sample of TETPPs by the composition of their home administrative unit (e.g., industry-focused, CTE-focused, education-focused), to determine whether this is associated with enrollment and graduation trends. Other potential indicators of program health should also be explored, such as affiliation with TEECA, the number of faculty, or the presence of graduate programs alongside undergraduate TETPPs.

Refining the List of Teacher Preparation Programs

As Love and Maiseroulle (2021, 2022) showed, and our study corroborates the many programs and routes for students to acquire TEE licensure through university-based programs. It is possible that additional programs may have been discontinued since Love & Maiseroulle's study and since our data were collected. In addition, while we were able to determine at a basic level which programs listed in the NCES database were still active TETPPs, a more thorough investigation is needed to determine the strength of these programs, including enrollment and graduation trends (and other possible indicators previously discussed), and curricular focus. In practice, this effort should ideally be consistent and ongoing at regular intervals. This effort could be conducted through strategic committee work within the Council on Technology and Engineering Teacher Education (CTETE) and would provide opportunities to strengthen the identity of the profession through increased collaborative effort and professional association among a larger number of TETPPs through organizations such as ITEEA.

Addressing the Demand Side of the Equation

Historic and current efforts to identify TETPPs and ascertain the status of the profession have tended to focus on the supply side of the supply-demand equation. In other words, most researchers have approached the issue by attempting to identify TETPPs directly by either contacting faculty in known teacher preparation programs periodically or by conducting searches and content analyses to identify previously unknown programs.

Another approach remains untried in our field but has been successfully implemented in agricultural education. Since 1965, agricultural education researchers have conducted a national supply and demand survey which, despite obvious challenges in obtaining complete data from all states, has produced beneficial data ranging from nationwide supply and demand for agriculture

teachers to program-specific data regarding the health of their teacher preparation programs (Foster, et al., 2025). One major component of this ongoing project approaches the problem of teacher preparation from the supply side of the equation by collecting state-level data on where agricultural education teachers are being hired, how they are obtaining certification/licensure (e.g., traditional teacher preparation programs versus alternative routes to licensure), and where the demand is greatest for agricultural educators at the K12 level. Similar research should be conducted in technology and engineering education, ideally with direct support from professional associations such as ITEEA through strategic committee work in CTETE.

In summary, these recommendations for future research suggest the need for a concerted effort, supported by professional associations such as ITEEA and affiliated councils such as the Council on Technology and Engineering Teacher Education, to produce a consistent and ongoing effort to gauge, and ultimately strengthen the health of our profession.

Conclusion

While there continues to be great concern for the vitality and strength of TEE, a dearth of largely untapped information continues to exist regarding technology and engineering teacher preparation programs. Although this study, building on previous work, has identified 84 active TETPPs, and assessed the basic enrollment and structure of several programs with recent TEECA affiliation, the structure and enrollment rates across TETPPs vary greatly from program to program. This inconsistency in program structure and visibility negatively impacts the profession.

Of the 84 programs that have been identified, only 43 are currently listed on ITEEA's website for teacher preparation programs. Our findings suggest the need for a concerted effort, supported by professional associations such as ITEEA to produce a consistent and ongoing effort to connect with, assess the health of, and develop a clear identity for technology and engineering education teacher preparation programs. We call for an updated accurate list of TETPPs as well as further studies evaluating the demand for technology and engineering educators in the nation.

Conflict of Interest Statement

The authors have no relevant financial or non-financial interests to disclose.

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Technical Socialization and Personality Traits as Predictors of the Need for Cognition in Technology Education?

Sebastian Goreth

Abstract

In a technology-driven society, the development of problem-solving skills among young students is becoming an increasingly important outcome in school education. At the same time, there is a well-documented decline in interest in technology among young people and persistent gender differences in science, technology, engineering, and mathematics (STEM) subjects. The present study examines the extent to which technical socialization and personality traits influence the Need for Cognition (NfC) among students by addressing the question: What correlations can be revealed between gender, personality traits, technical socialization and NfC? In answering that question, the research aim is to use the insights gained from these correlations to best support the development of problem-solving abilities among students of both genders in all technology subjects, but specifically that of Technology Education and/or Design and Technology Education.

NfC describes the stable tendency to engage in cognitively demanding tasks and to experience thinking processes as intrinsically satisfying. In a quantitative online questionnaire secondary school students (N = 614) were asked about their technical socialization, personality traits (Big Five), and the extent of their NfC. The data were evaluated using t-tests and variance analyses.

The results show gender-specific differences in technical socialization, but no differences in NfC levels. Openness to experience is the only significant predictor of NfC. The findings provide starting points for teachers of Technology Education and/or Design and Technology Education with regard to helping ensure gender-sensitive implementation of school programs.

Keywords: Gender and Technology, Need for Cognition, Technical Socialization, Technology Education, Design and Technology Education

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Introduction

The use of technical artifacts, which is often reduced to mere operation, is omnipresent in everyday life. In contrast, there has been a continuous decline in interest in technology among children and young people for years (Acatech, 2011; Tenberg, 2016; Acatech & Köber-Stiftung, 2021). Both the intensive use of technical systems in everyday life and the working world, and the declining interest in technical issues have not changed fundamentally in recent years. In addition, there are clear, largely unchanged gender-specific differences in career

preferences in the science, technology, engineering, and mathematics (STEM) fields (Acatech & VDI, 2009; Sachs, 1987; Bundesministerium für Bildung und Forschung, 2018; van Tuijl & van der Molen, 2016). School education therefore has the task of exploiting all possibilities to attract all the young people to technology subjects (Goreth, Krebs & Windelband, 2021).

The aim of Technology Education (TE) and/or Design and Technology Education (DTE) must therefore be to educate responsible citizens for a technologically dominated world (Pasternak, 2013). Given this aim, both TE and DTE should always be understood as part of general education (Ropohl, 2009) and should not be geared towards specific groups, such as boys. This is confirmed, among other things, by the choice of subjects in secondary schools in recent years (in Germany, for example: Statistisches Landesamt Baden-Württemberg, 2019; in Austria, for example: Sutterlüti, 2013). In contrast to Technology and Engineering Education (TEE) and the field of vocational training, this article focuses on Technology Education (TE), also known as Design and Technology Education (DTE). In German-speaking countries, there are a variety of terms for this general education subject (e.g., "Technik" = "technology", "Werken" = "crafts", "Technik und Design" = "technology and design") that are all distinct from the engineering sciences and are intended solely to provide pre-vocational orientation. However, the specific content of the subject (e.g., "Technik und Design" = "technology and design" in Austria) varies across the levels (primary, secondary level 1, and secondary level 2), though what they all have in common is that technical problems are solved while practicing rudimentary skills and procedures (creative design processes and the development of problem-solving skills, rather than the teaching of specialized engineering or vocationally qualifying content).

Education in a modern sense can promote the independence and self-determination of a person (Raithel, Dollinger & Hörmann, 2009), which will become increasingly important in relation to technology (Schlagenhauf & Wiesmüller, 2018). Dealing with technical issues is a central component of modern education and contributes significantly to preparing young people for the demands of today's life in society, work, and economy (Penning, 2023; Schlagenhauf & Wiesmüller, 2018; Stemmann & Lang, 2014).

Theoretical Background

Technology education fosters responsible citizens who can navigate a technology-driven world and help shape it (Goreth, 2020). In addition, people are given the tools to engage intelligently and thoughtfully with the world around them (National Academies of Sciences, Engineering, and Medicine, 2002), or to shape the world around them and solve problems (International Technology Education Association, 2007).

Problem-solving skills are now considered essential in order to be prepared for future developments and to solve problems creatively in unknown situations

(Organization for Economic Co-operation and Development, 2014). Need for Cognition (NfC) is essential in fostering problem-solving skills. This is because in an increasingly digitalized and automated everyday reality, the ability to solve practical problems creatively and purposefully is becoming particularly important (Koçoğlu & Kanadlı, 2025). Within STEM education, self-concept shows significant gender differences, often dependent on actual skill levels (Jann & Hupka-Brunner, 2020) that alongside parents and internships, have a clear influence on the choice of a technical profession or course of study (Brämer, 2019; Acatech, 2011).

The following section discusses aspects of learning (creativity, problem-solving, motivation) and the Need for Cognition (NfC) in the context of technology education. Specifically, in addition to personality traits and technical socialization to what extent can NfC also be considered an influencing factor in Technology Education? While the construct of technical socialization used here, in the strict sense, aligns with the German-speaking approach, which emphasizes technical interest and technical experiences, describes how people are introduced to technical activities and objects through family, and leisure time, and is distinguished from technological socialization, the NfC is regarded as a construct that describes an individual's stable intrinsic motivation to engage in and enjoy cognitively demanding thinking and problem-solving activities. Both are essential aspects of Technology Education.

Personality Traits (BIG-5)

The Five Factor Model (FFM), often referred to as the Big Five, is a widely accepted psychological framework designed to comprehensively describe human personality through five broad dimensions: Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism. By measuring these distinct traits, the model maps an individual's enduring behavioral patterns, emotional tendencies, and interpersonal styles. From an educational perspective, administering the FFM allows educators to identify student learning styles, predict academic performance (i.e., high conscientiousness strongly correlates with academic success) and anticipate potential behavioral challenges. These insights can then be used to tailor instructional methods, develop targeted socio-emotional interventions, and provide instructional strategies to support a student's natural strengths and dispositions.

The interaction of the five dimensions, which can vary in intensity but are always present, represent individual behaviors and experiences (Gerlitz & Schupp, 2005). In English-speaking countries, the acronym OCEAN is used as a mnemonic to remember the five factors, which are synonymous with the German psychological terms (Neyer & Asendorpf, 2018). Based on the work of Neyer & Asendorpf (2018), these five dimensions can be described as:

Openness to experience encompasses characteristics such as intellectual curiosity, artistic sensibility, and creativity and is positively related to intelligence and education.

Conscientiousness, in contrast, is characterized by a sense of order, perseverance, and reliability.

Extraversion is characterized by excitability, sociability, a high level of activity, and low inhibitions.

Agreeableness is reflected in friendly, helpful, and warm behavior toward others.

Neuroticism describes emotional instability characterized by nervousness, anxiety, and mood swings.

Relevant to Technology Education, a large-scale study of personality profiles in 263 occupations (Anni et al., 2025) showed moderate differences in the five-factor model of personality for work-oriented, manual-technical occupations (e.g., tailor, mechanic, shoemaker, roofer, painter, etc.). On average, these occupational fields scored below average to average on the dimensions of openness and extraversion, which may reflect a stronger orientation toward practical, proven, and regulated working methods. The scores for the remaining Big Five personality dimensions were predominantly within the overall average range. Research conducted by Feist (1998) demonstrated that personality traits such as openness to experience, conscientiousness, and extraversion are linked to creativity, problem-solving ability, motivation to learn, and interest in technology, and are therefore highly relevant to the teaching of technical subjects. In general, creative people are more open to new experiences, less conventional and less conscientious, more self-confident, more self-accepting, more goal-oriented, more ambitious, more dominant, more hostile, and more impulsive. In light of such findings, Technology Education should be well-positioned to promote technical socialization by instructionally incorporating openness and extraversion as integral elements of design, creativity, and problem-solving.

Technical Socialization

Technical socialization describes "how people become familiar with technology from early childhood through adolescence, vocational training, and university studies to their careers" (Acatech & VDI, 2009, p. 25, translated by the author). Acatech—the German Academy of Science and Engineering (Deutsche Akademie der Technikwissenschaften)—and the Association of German Engineers (Verein Deutscher Ingenieure, VDI) are among the most important German institutions dedicated to promoting science, engineering, and Technology Education. "Successful technology socialisation, i.e., obtaining an early understanding of the functions, potential and opportunities of technology, and the risk it poses, begins at home. By promoting fun and curiosity through a playful, experimental approach to technology and natural science, it is possible

to awaken an interest in technological matters while engendering greater openness toward technology" (Acatech & VDI, 2009/2010, p. 9). The parental home, kindergarten, and school are key locations where technical socialization takes place. However, friends and the media may also exert a formative influence on interest in technology (Acatech & VDI, 2009/2010). When examining technical socialization, it is particularly relevant to consider the extent of technical and scientific engagement in childhood, as interest and cognitive openness toward technical and scientific phenomena are known to develop at an early age (Acatech & VDI, 2009).

The research questionnaire administered by the Nachwuchsbarometer der Technikwissenschaften, used various items to assess the technical socialization of schoolchildren, students, engineers, and scientists (N = 12,846) (Acatech & VDI, 2009). These items covered areas such as game and object references in the technical and scientific fields or parental support. Among the most prominent results generated from this survey research was that children rarely engage with questions of how things work in everyday technical situations. Students interested in technology reported more frequent contact with technical games and objects than the general student population. Additionally, gender-specific differences in interest in technology and science were observed: male students scored higher in all areas examined (including aerospace engineering and electrical engineering) with the exception of medical technology and biology. In addition, further review of the literature revealed several studies that describe the influence of family, school, and extracurricular experiences on interest in technology, self-concept, and educational decisions, as well as those that address gender-specific socialization processes. Sociality is strongly associated with femininity and technology with masculinity (Faulkner, 2007). Since the consolidation of interests is usually complete by age 14 (Archer et al., 2010), early socialization is thus relevant to interest in technology in order to enhance students' academic success.

Need for Cognition

Need for Cognition (NfC) refers to a cognitive personality trait, defined as the stable tendency to actively seek out mentally challenging tasks and to enjoy engaging in them, as well as an individual's intrinsic motivation to engage in thought processes and resolve ambiguities quickly and permanently (Cacioppo & Petty, 1982). Cohen et al. (1955) originally defined NfC as "the need to structure complex situations in a meaningful, comprehensive way" (translated by the author) and associated it with intolerance of ambiguity. NfC thus encompasses two different dimensions: the need for structure (seizing: grasping onto the first plausible solution) and determination (freezing: locking onto that choice without further evidence) (Webster & Kruglanski, 1994; Liu et al., 2018). Technology Education is a subject where tasks usually provide complex problems, where seizing and freezing are common cognitive approaches novice

designers use to achieve problem solving when engaged in design-based learning, open-ended technological challenges, the engineering design processes, maker education, and authentic real-world problem-solving tasks.

People with high NfC scores find intellectual challenges satisfying and enjoy investing cognitive effort: they enjoy debates, problem solving and tend toward deep information processing (high elaboration) (Cacioppo & Petty, 1982). They actively seek information and reflect on it thoroughly. NfC explains systematic differences in people's engagement, particularly regarding cognitively challenging and strenuous activities (Cacioppo et al., 1996). In a school context, students with high NfC also display more engagement when they perceive a task as challenging (Steinhart & Wyer, 2009). In line with this finding, NfC predicts an individual's ability and interest to learn, especially in more cognitively demanding learning environments (Colling et al., 2022). Technology Education is a subject where intellectual challenges and imposed cognitive demands (Wells, 2016) are prevalent, because of the ongoing, continuous need for planning, adapting, thinking and doing as integral elements of design-based learning.

While people with high NfC tend to engage in more in-depth analysis and reflection, people with low NfC prefer quicker, predefined solutions (Li & Browne, 2004). Goswami (2025) examined the link between NfC and artificial intelligence (AI): there was a significant negative correlation between NfC and the use of ChatGPT, while NfC had no significant influence on general attitude toward AI. It can be concluded that people with lower NfC tend to rely on AI to find quick solutions, while people with higher NfC, due to their reflective thinking, tend to question AI and approach it critically. There is a correlation between ChatGPT use and NfC of $r = -0.33$ (Goswami, 2025). The implication is that students with lower and higher NfC would approach and carry out designerly tasks differently in Technology Education.

Furthermore, individual differences in NfC are independent of gender, socioeconomic status (SES), or cultural background (Bergold & Steinmayr 2023; Bertrams & Dickhäuser 2010; Colling et al. 2022; Preckel & Strobel 2017). A meta-analysis by Liu & Nesbit (2023) examined how high NfC scores affect learning performance, creativity, and problem-solving skills. Their results found there was an average correlation of $r \approx 0.20$ between NfC and academic performance indicators, with this correlation tending to be stronger among older or more advanced learners. Matthes et al. (2025) found that NfC is a positive predictor of academic interest, but that interest itself is not a predictor of high levels of NfC. In other words, individuals with high NfC often achieve better academic results, not only because they may be more cognitively gifted, but because their need to think has an independent positive influence. Interestingly, learners with high NfC show increased effort and engagement, especially when they expect a task to be difficult or demanding. They are less deterred by challenging tasks and approach them with greater commitment. Accordingly,

their learning gains benefit significantly from high NfC, especially in cognitively demanding learning environments, e.g., when dealing with complex problems or higher academic requirements (Liu & Nesbit, 2023).

Another correlation between high NfC and academic performance points to a particular development of skills in problem-solving processes (Strobel et al., 2024). People with high NfC actively seek solutions and explanations. They benefit from their critical perception as effective problem solvers and are particularly interested in why a problem solution works. This can provide insights for future problem-solving activities and the development of learning strategies, which can consequently lead to more effective performance (Coutinho et al., 2005).

In summary, the literature shows that individuals with high NfC prefer complex cognitive challenges, take a more analytical approach, and persevere more in tackling demanding tasks (Cacioppo & Petty, 1982; Cacioppo et al., 1996). These characteristics are particularly significant given technology-, engineering-, and design-oriented learning environments impose cognitive demands on learners, underscoring the relevance of this construct to the present study. This is especially evident when considering the overarching subject-area aim of developing problem-solving competence, along with its curricular objectives.

Method

Research Design

Enjoyment and engagement in cognitive tasks are reflective of the Need for Cognition (NfC) and considered to have an influence on problem-solving skills and creativity. Taking this into account, the current study focused on assessing the influence of key factors on students' NfC. To do so, the study employed a quantitative, non-experimental cross-sectional survey design. Data were gathered using an adapted composite questionnaire comprised of validated Likert-scale items selected to measure the influence of key factors on students' NfC. Results of data analysis provide insights into key influential factors such as the participants' experience with technology (e.g., previous experience with technical games and objects, interest in technology and science fostered by the family environment) and personality traits (BIG-5 personality factors) with the goal of identifying correlations with Need for Cognition.

The research questions guiding this study were:

1. What correlations can be revealed between the Need for Cognition (NfC), experienced technical socialization, and the Big Five personality traits among students?
2. To what extent do these correlations differ by gender?

The following hypotheses were tested:

H1. Cognitive need is influenced by experienced technical socialization (the degree of technical play and object references and parental support) as well as personality traits.

H2. Male students show higher values in experienced technical socialization (both in terms of technical play and object references and in terms of parental support) than female students, as measured by self-assessments.

H3. There is no difference in the extent of Need for Cognition between male and female students.

In answering the research questions and addressing the hypotheses, this study aims to:

- provide insights for teachers on how to design instruction for technology classes taking into account students' NfC,
- use the results to encourage teachers to develop instructional strategies that intentionally promote cognitive demand.

Instrumentation

Data were collected as part of the DIGIdat research project, which focused on the subjective perception of indoor air quality at various measurement time points. The students generated a personal ID at the beginning of the project. This ensured anonymity while simultaneously allowing the responses to be assigned to the various measurement times and the aggregated test duration to be distributed across the lessons. One subproject involved identifying the students' interests and technical backgrounds.

For the present study, the questionnaire was developed to include a socio-demographic section to determine age, gender, and first language. In addition, the questionnaire contains questions on technical socialization based on the questionnaire items from Acatech and VDI (2009), which were used for surveys as part of a report in the Nachwuchsbarometer Technikwissenschaften (N = 12,846). Twelve items on *play and object references*, two items on *parental support of interest*, and twelve items on the *image profile of technical and scientific professions* among students were selected for this purpose (Acatech & VDI, 2009). Various tried-and-tested questionnaire items already exist for the collection and evaluation of personality factors based on external or self-perception (Neyer & Asendorpf, 2018). The Big Five Inventory (BFI) versions by Gerlitz and Schupp (2005) may be used freely (Neyer & Asendorpf, 2018). The Big Five Inventory-Short Form (BFI-S) developed by Gerlitz and Schupp (2005) was used to examine the personality factors of the students. The test for measuring enjoyment and engagement in cognitive tasks (Need for Cognition; NfC for short) is based on a test developed by Cacioppo & Petty (1982), in which 45 test items on a 9-point Likert scale were tested on a homogeneous

group (Cacioppo & Petty, 1982). The tendency to experience positive feelings towards conscious analytical activities is distinct from cognitive abilities and has a one-dimensional structure. The test, which was adapted into German by Preckel (2014), contains items, some of which were revised and validated with 20 students using a 5-point Likert scale (1 = "strongly disagree" to 5 = "strongly agree"); it also exhibits a unidimensional structure (Preckel, 2014).

The selection of items and the development of the NfC Influence Questionnaire (NfC-IQ) instrument were carried out by an interdisciplinary team of four experts from the DIGIdat project (2 educational researchers, 1 pedagogical-content researcher, 1 subject-specific researcher). The item selection process took place in several steps. After the expert team reviewed potential instruments, their use was discussed and subsequently selected based on possible correlations derived from theory. The structure of the NfC-IQ was comprised of the following items:

- Need for Cognition – 19 items: 5-point Likert scale (1 = 'Strongly disagree' to 5 = 'Strongly agree') (Cronbach's $\alpha = 0.80$, with decoded items), example item: I enjoy coming up with solutions to problems.
- Big Five Inventory-Short Form – 15 items: 5-point Likert scale (1 = 'Does not apply at all' to 5 = 'Applies completely') (Cronbach's $\alpha = 0.69$ across all characteristics, which is within the expected range for the short scale, given the various dimensions), example item: I am someone who completes tasks effectively and efficiently.
- Acatech/VDI (technical socialization/play and object references – 12 items: 6-point Likert scale (1 = 'Does not apply at all' to 6 = 'Applies completely') (Cronbach's $\alpha = 0.90$), example item: How often do you engage with these things?
- Acatech/VDI (technical socialization/parental encouragement – 2 items: 6-point Likert scale (1 = 'Does not apply at all' to 6 = 'Applies completely') example item: My family encourages my interest in technology.
- Acatech/VDI (characteristics of technical professions) – 12 items: 6-point Likert scale (1 = 'Does not apply at all' to 6 = 'Applies completely') example item: In your opinion, what characteristics do technical professions have?
- Sociodemographic data – 3 items: (age, gender, first language)

The NfC-IQ was administered via the online platform soscisurvey to students in schools from the DIGIdat project who voluntarily completed the questionnaire. The NfC-IQ questionnaire took approximately 15 minutes to complete.

Data analysis was primarily performed using t-tests for independent samples and one- or two-factor analyses of variance (ANOVA) to test the hypotheses. The questionnaire mainly contained Likert scales, which allows for

the calculation of means and standard deviations as well as the comparison of groups using t-tests and ANOVA. The t-tests were used to test mean differences between two independent groups, for example, in the analysis of gender-specific differences. For comparisons of more than two groups, for example regarding the predictor of Need for Cognition, one-way analyses of variance (ANOVA) or correlation analyses between variables were performed. The statistical analyses were conducted with a significance level of $p < .05$.

Procedures

Participants

Prior research indicates interests and career-related orientations largely stabilize by around age 14 (Archer et al., 2010). Furthermore, the period prior to age 14 is considered particularly significant for the development of technical interests and socialization-related attitudes. Thus, students in lower and upper secondary school from a total of ten schools in Tyrol were targeted for participation in this survey research. Participants were drawn from both middle schools and academic high schools, as well as one higher school. Participating classes were predominantly eighth grade. Moreover, taking into account prior research by Archer et al., this study deliberately focused on students aged 12 to 13, as this age group represents a pivotal phase of Technology Education in lower secondary schools of Austria. At this age, classroom instruction increasingly focuses on technical problem-solving, design processes, and fundamental technical and creative skills in accordance with curriculum guidelines.

Table 1

NfC Participants: Student Volunteers per DIGIdat School Type

Code	DIGIdat School Type	# NfC Volunteer Participants
	Unclassified	16
AHS	Academic High School	73
AHS	Federal Academic High School I	23
AHS	Federal Academic High School II	77
AHS	Federal Academic High School III	63
BHS	Higher Technical School	67
MS	Middle School I	129
MS	Middle School II	71
MS	Middle School III	59
MS	Practical Middle School	23
MS	Middle School IV	13

Before the project began, the DIGIdat project leadership selected the participating schools, taking care to assemble a sample that was as heterogeneous as possible. Schools with different structural conditions (transit traffic vs. no transit traffic through the Alpine valley) and varying levels of equipment (ventilation system present vs. no ventilation system present) were considered. In addition, care was taken to ensure a balanced ratio between urban and rural schools as well as among different types of schools (Table 1). The goal of this selection was to reflect the diverse perspectives and conditions of the participating schools with regard to indoor air quality. Participation in the research project was voluntary and not mandatory for the schools.

NfC-IQ Questionnaire Administration

Administration of the NfC-IQ was conducted via the SoSciSurvey platform. Administration took place over a 1-year period between spring 2023 and 2024 during school hours and was supervised on-site by the respective teachers. Participation was voluntary, and those students choosing to participate completed the questionnaire independently on tablets or iPads.

Prior to questionnaire administration, the Ethics Committee of the Lehrerinnenverbund West of the Universities was asked to raise any potential concerns. All data collected were completely anonymized and had no influence on grades assigned by teachers. Questions regarding cultural backgrounds were deliberately not included. The DIGIdat research project (SPSC_01_154) is funded and monitored by the BMBWF (Federal Ministry of Education, Science, and Research) through the Citizen Science Sparkling 2.0 program. The consent forms from the legal guardians of all participants were obtained.

Collected data were prepared for statistical analysis and subsequently analyzed using appropriate methods. The goal of data preparation was to prepare the collected variables for statistical analysis and to create composite scales for the constructs under investigation from the items used. The statistical analysis was performed using IBM SPSS Statistics 32.0 software.

All available data sets were included in the present study. Given data collection for the DIGIdat research project took place over several rounds of questionnaire administrations, complete data sets were not available for all participants at every measurement point in time. However, because the present study focused on the aggregated scale scores of the individual constructs, even incomplete data sets could be included in the analysis. Therefore, all available data on the relevant items were used for the analysis.

Prior to the statistical analysis, negatively worded items on individual scales were recoded. This was necessary because, for these items, a high level of agreement does not automatically reflect a high level of the respective construct. For example, a high level of agreement with a negatively worded Need for Cognition item such as “I don’t enjoy thinking” would indicate a lower level of Need for Cognition. To ensure that all items within a scale can be interpreted

consistently, these statements were reversed accordingly. The recoding affected a total of four items on the BFI-S form and eight items on the Need for Cognition questionnaire.

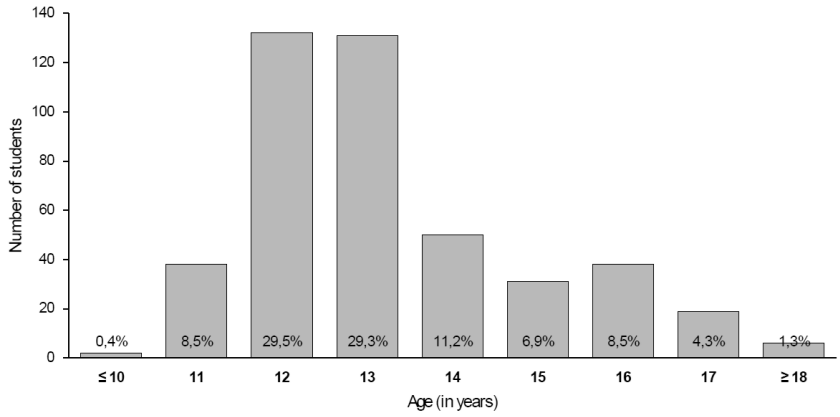
Results

Participant Demographics

Participants in this study (N = 614) ranged in age from 10 to 18 years of age (Figure 1), with the largest portion being those aged 12 to 13 (≙ 58.8%). The distribution of males and females was 56.3% and 43.7% respectively, and among them German was the predominant first language (77.7%).

Figure 1

Age distribution of student participants

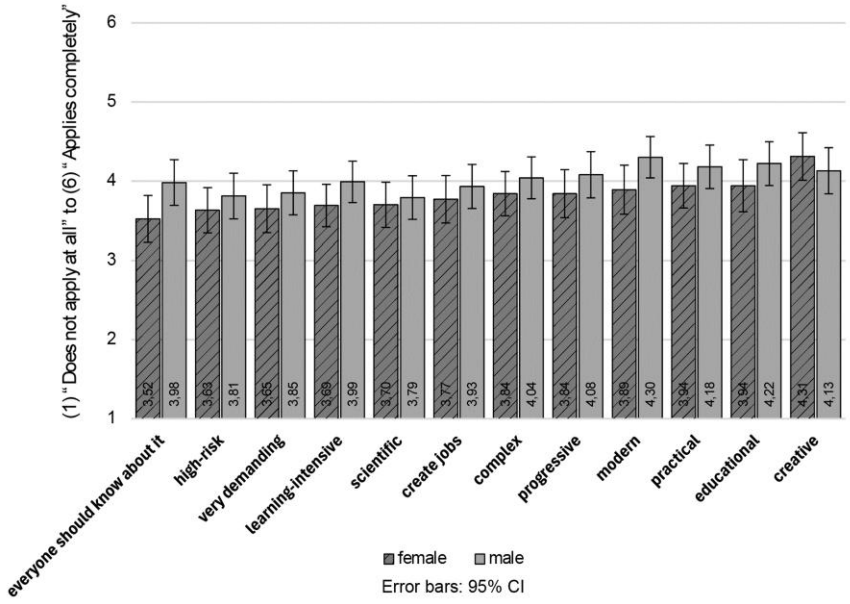


Characteristics of Technical Professions

Items assessing characteristics of professions (Figure 2) indicate relatively homogenous responses between genders. It can be noted that, on average across both genders, the lowest scores are found in the categories everyone should know about it (M = 3.84, SD = 1.42) and high-risk (M = 3.75, SD = 1.38) and the highest scores in educational (M = 4.13, SD = 1.41) and creative (M = 4.22, SD = 1.41). Between these extremes are scores such as complex (M = 3.99, SD = 1.30) or create jobs (M = 3.91, SD = 1.38).

Figure 2

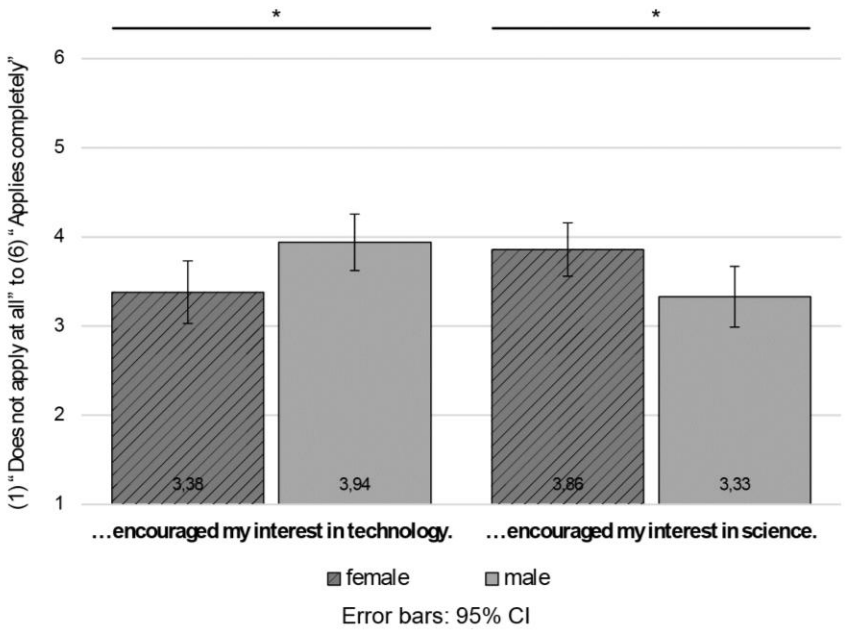
Characteristics of the Profession (six-point Likert scale from 1 = "Does not apply at all" to 6 = "Applies completely")



Parental support for the profession (Figure 3) is somewhat gender-dependent. The data indicate that female participants tend to be more supportive of science (M_{Girls} = 3.86, SD = 1.22) than their male counterpart (M_{Boys} = 3.33, SD = 1.72) at $t(158) = 2.27$; $p < 0.05$; $d = 0.37$), while male participants are more likely to be encouraged towards technology (M_{Boys} = 3.94, SD = 1.61) than female participants (M_{Girls} = 3.38, SD = 1.44) at $t(163) = -2.26$; $p < 0.05$; $d = -0.36$).

Figure 3

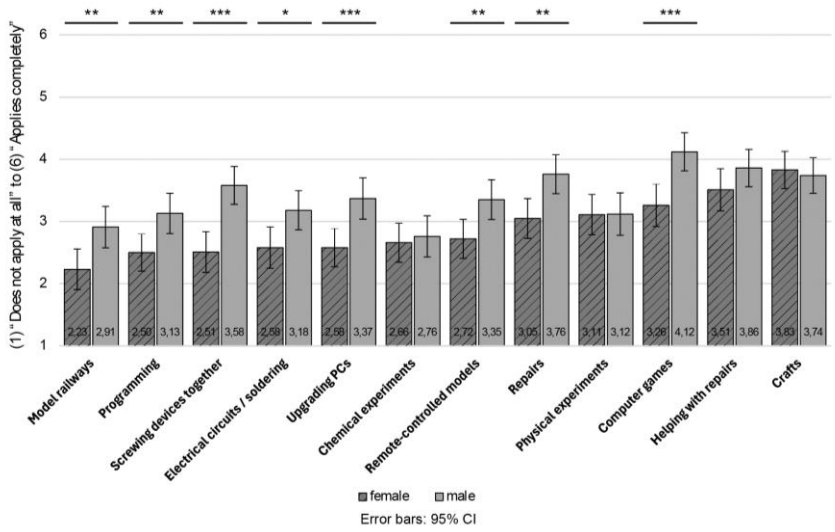
Parental support for students (six-point Likert scale from 1 = "Does not apply at all" to 6 = "Applies completely")



The difference in parental support for students is also evident in specific play and object references (Figure 4). While crafts, physical experiments, chemical experiments, and helping with repairs show only descriptive differences, the situation is different when it comes to technical and IT-related references.

Figure 4

Technical Socialization through Play and Object References (six-point Likert scale from 1 = "Does not apply at all" to 6 = "Applies completely")

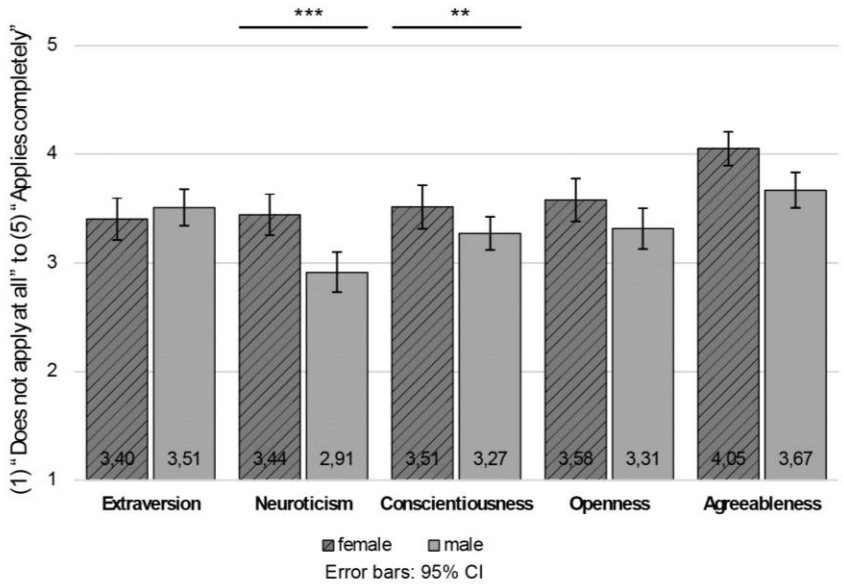


During their childhood, male students were more likely to engage in activities such as model railways (M_{Boys} = 2.91, SD = 1.74), electrical circuits/soldering (M_{Boys} = 3.18, SD = 1.66), assembling devices (M_{Boys} = 3.58, SD = 1.60) and repairs (M_{Boys} = 3.76, SD = 1.70) than female students (M_{Girls} = 2.23, SD = 1.34, M_{Girls} = 2.58, SD = 1.36, M_{Girls} = 2.51, SD = 1.39 & M_{Girls} = 3.05, SD = 1.32) at $t(160) = -2.87$; $p < 0.01$; $d = -0.45$, $t(168) = -2.45$, $p < 0.05$; $d = 0.39$, $t(169) = -4.54$, $p < 0.001$; $d = 0.72$ & $t(158) = -2.45$, $p < 0.01$; $d = 0.49$ (Figure 4).

Figure 5 depicts analyses of personality trait data collected from the Big Five Inventory-Short Form (BFI-S). The results show that female students score higher than male students in the areas of neuroticism (M_{Girls} = 3.44, SD = 0.86) and conscientiousness (M_{Girls} = 3.51, SD = 0.91) compared to male students (M_{Boys} = 2.91; SD = 0.88 & M_{Boys} = 3.27, SD = 0.73) at $t(168) = 3.92$; $p < 0.001$; $d = 0.60$, $t(165) = 1.91$, $p < 0.01$; $d = 0.30$.

Figure 5

BIG-5 Personality Traits (five-point Likert scale from 1 = "Does not apply at all" to 5 = "Applies completely")



In addition, there are no significant differences in other areas, such as Openness (M_{Girls} = 3.58, SD = 0.89, M_{Boys} = 3.31, SD = 0.88). The mean value for the Need for Cognition dimension is for the female students (M_{Girls} = 3.20, SD = 0.55) and for the male students (M_{Boys} = 3.13, SD = 0.55). This results in a range of R = 3.47, and the results can be assumed to be normally distributed (kurtosis = 0.74 & skewness = 0.27).

Results from an ANOVA (Figure 6) shows that neither parental support experienced in science and technology (technical socialization) nor the play and object references (technical socialization) nor gender and age have a significant influence on the Need for Cognition. Within the personality traits, it can be seen that openness to experience (open-mindedness) has a significant influence on the Need for Cognition $F(118) = 1.56$, $p < 0.05$.

Table 2

Results of an ANOVA (Need for Cognition)

Predictor	*df*	*F*	*p*
Age	78, 219	0.92	.661
Gender	79, 223	0.86	.774
Parental support: Interest in technology	49, 49	0.89	.659
Parental support: Interest in science	49, 47	1.11	.359
Openness	52, 66	1.55	.045
Conscientiousness	54, 66	1.17	.274
Extraversion	53, 69	1.25	.190
Agreeableness	52, 69	1.09	.370
Neuroticism	54, 69	0.78	.826
Technical socialization: Game and object references	50, 52	0.82	.764

Discussion

Problem-solving competence is widely regarded as one of the central educational goals of Technology Education or Design and Technology Education because it enables learners to participate responsibly in a technology-driven society (Organization for Economic Co-operation and Development, 2024). Against this background, the present study investigated whether students' NfC is associated with technical socialization and personality traits.

The first important finding concerns technical socialization. Consistent with previous studies (Acatech & VDI, 2009; Archer et al., 2010), boys reported significantly more technical play experiences, object-related activities, and parental encouragement in technology than girls. These results confirm that gendered patterns of technical socialization remain stable despite numerous initiatives promoting girls in STEM over the last decades. The absence of gender differences in NfC is equally noteworthy, because girls reported substantially lower levels of technical socialization.

A second and more important contribution to Technology Education concerns the role of NfC. In contrast to widespread assumptions that stronger technical experiences automatically foster cognitive engagement (Acatech, 2011), neither technical socialization nor parental encouragement significantly predicted NfC. Instead, openness to experience emerged as the only significant predictor. This finding suggests that NfC represents a relatively independent

disposition that cannot simply be developed through increased exposure to technical artefacts or technical activities.

Perhaps the most important contribution of this study lies in the finding that openness to experience—but not technical socialization—predicts NfC. From a Technology Education perspective, this indicates that NfC represents a distinct construct that cannot simply be explained by previous technical experiences. The finding that openness to experience predicts NfC also has implications for instructional design. Technology education should not only provide opportunities for hands-on activities but should deliberately create learning environments that stimulate curiosity, exploration, creativity, and reflection (Goreth, Krebs & Windelband, 2021). Design-based learning, open-ended technological challenges, engineering design processes, maker education, and authentic real-world problem-solving tasks appear particularly suitable because they require students to evaluate multiple solution pathways rather than reproduce predefined procedures. Such approaches may strengthen students' willingness to invest cognitive effort even if NfC itself is considered a relatively stable personality-related disposition.

Conclusion

From a theoretical perspective, the juxtaposition of technical socialization and NfC provides valuable insight. Specifically, technical socialization explains how learners become familiar with technology through family, school, peers, and everyday experiences, whereas NfC describes an individual's intrinsic willingness to engage with cognitively demanding problems. Considering both constructs simultaneously provides the opportunity for researchers in Technology Education research to differentiate between external learning opportunities and internal NfC. Doing so would contribute to a more comprehensive understanding of why learners with similar technical experiences may nevertheless approach technological problem-solving differently.

The findings also provide important implications for educational practice. Rather than focusing exclusively on increasing students' exposure to technology, teaching should deliberately promote learning environments that stimulate curiosity, intellectual exploration, creativity, and sustained reflection.
Finally, the study highlights several promising directions for future research. Longitudinal investigations are needed to examine how NfC develops throughout school education and how it interacts with technical experiences over time. Integrating these perspectives could contribute to more comprehensive explanatory models of learning in Technology Education.

Limitations

Several limitations should be considered when interpreting the findings. First, the study is based on a regional sample of secondary school students from Tyrol (Austria). Although the sample size is substantial, the educational context,

curricular framework, and cultural characteristics may differ from those in other countries. Consequently, the transferability of the findings to other educational systems should be made with caution.

Second, the study employed a cross-sectional design, which does not allow causal conclusions. While openness to experience was identified as a significant predictor of Need for Cognition (NfC), it cannot be determined whether personality characteristics promote cognitive motivation or whether repeated engagement with cognitively demanding learning environments influences personality-related dispositions over time. Longitudinal studies are therefore needed to better understand developmental trajectories.

A further limitation concerns the measurement approach. Technical socialization was assessed using retrospective self-reports about childhood experiences and parental encouragement. Such measures may be influenced by memory effects or subjective perceptions. Likewise, the study focused on motivational dispositions rather than actual technological competence, engineering design performance, or observable problem-solving behavior. Future studies should therefore combine validated motivational scales with performance-based assessments and authentic design tasks.

Conflict of Interest Statement

The authors have no relevant financial or non-financial interests to disclose.

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The Perception of Technological Models among Upper Secondary School Students

Ümit Köycü, Marc J. de Vries, Jonas Hallström

Abstract

Globally there is rising interest for introducing engineering education as part of general secondary education. Across Europe in particular, several curricular reforms and policy initiatives have emphasized the integration of engineering concepts into general secondary education as part of broader STEM agendas (Moore et al., 2014; European Commission, 2015; Kelley & Knowles, 2016; Nia & de Vries, 2017; Demirci & Özyürek, 2024; Ahmad et al., 2026). Such developmental trends reflect a growing recognition that engineering literacy is relevant for all students, not just those pursuing technical careers. Consequently, understanding how students conceptualize central constructs within engineering education, such as technological models, becomes increasingly important. Given that technological models is a central construct in engineering education (Rossouw et al, 2011), the impetus for this research was to establish a baseline regarding perceptions of the technological models construct held by students at the upper secondary level.

The research presented in this article followed a mixed method design implemented within two international schools engaging a total of 345 students from 13 language backgrounds. Qualitative data were collected from 72 students through written and interview responses to questions asking participants to describe what they think a technological model entails. Quantitative data were subsequently collected from 338 students through a questionnaire consisting of 30 True/False items asking them to indicate if the picture in the item corresponded to their concept of a technological model. A factor analysis was carried out to reveal the dimensions of the concept among the students. Findings indicate that in contrast to previous studies among lower secondary school students, a distinct concept of a technological model was found among the secondary participants in this study. Furthermore, differences in model concepts held by male and female students at the lower secondary level revealed by prior research, were not found among the secondary level students in this study. Based on findings, the study revealed that the concept of technological models held by secondary level students indicated a reasonably correct understanding, although predominantly visual and product-oriented.

Key words: Concepts, technological models, engineering, higher secondary education

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Introduction

In Technology Education, both skills and corresponding concepts such as systems, functions, and models (Rossouw et al, 2011) should be the intent of instruction (Bellanca & Brandt, 2010). To design instruction that will adequately connect skills and concepts, educators would first assess preconceptions held by their students. Considerable research has been conducted regarding the assessment of preconceptions held by students of models in science education (e.g., AAAS, 2001; Grosslight et al., 1991). In stark contrast, empirical research explicitly addressing preconceptions held by students of technological models in engineering and technology education remains comparatively limited (e.g., Nia & de Vries, 2017).

Learning about concepts logically should be started in junior high school, but there are more opportunities in senior high school given students at that grade level are generally better able to think abstractly. Creating sound instructional materials for teaching engineering in upper secondary schools requires first carefully examining the concepts and abstract imagery students currently hold regarding key targeted learning outcomes for the subject (Rossouw et al., 2011). In engineering education, one key learning outcome is having students develop a reasonably correct understanding of technological models. To address this initial step in instructional design, the current study was conducted to ascertain preconceptions of technological models currently held by students in upper secondary education. The definition of a technological model adhered to in this study is *a representation constructed to support the analysis, design, prediction, optimization, or communication of a technological system*.

The current study was conducted in two European international secondary schools with linguistically and culturally diverse student populations. These schools follow harmonized curricula attracting students from multiple national backgrounds, which may influence students' prior exposure to engineering concepts and technological systems. While this context provides a heterogeneous sample, it may also introduce specific contextual characteristics that should be considered when interpreting the findings. Within this context, the aim of this research was to ascertain the preconceptions of technological models held by high school students prior to these concepts being introduced in the engineering curriculum. Understanding these preconceptions is crucial given the growing interest in many countries for integrating engineering into secondary education as a means to enhance technological literacy. By aligning the design of instruction based on an accurate assessment of student preconceptions, we can better ensure that the introduction of engineering concepts will be pedagogically sound.

Literature Review: Perceptions of Models and Modelling in Science and Engineering

Scientific Modelling

According to Gilbert (2004), models and the process of modeling are central to making science education more authentic and meaningful. Students should recognize that models can serve different purposes and come in diverse forms, including physical models, diagrams, formulas, and maps. Gilbert emphasizes that models in science are not exact copies of reality but tools that help explain and predict phenomena. Specifically, their primary function is not to serve as an exact replica, but to instead play various roles, such as facilitating communication, enabling experimentation, and enhancing understanding. In addition to their roles in understanding and experimentation, Gilbert suggests models can be categorized into five different representational modes: the concrete or material, the verbal, the symbolic, the visual, and the gestural. This variety of functions and representations highlights the broader role of models beyond simple replication.

A substantial body of research has examined the teaching and learning of specific scientific models, including particle models (Hitt & Townsend, 2015), molecular models (Treagust et al., 2002), and atomic models (Justi & Gilbert, 2002). In contrast, fewer studies such as that conducted by Grosslight et al. in 1991 have focused explicitly on students' understanding of the modelling process itself or on students' broader conceptions of models and their epistemological status in science (Grosslight et al., 1991). The students in the latter study often held views that corresponded to a simplistic epistemology. That is, the students usually regarded models as exact copies of reality, albeit on a different scale. However, the older students appeared to understand, that models are designed for specific purposes, and that a model may change over time, for example when new empirical data are analyzed. The functions of models in explaining and predicting observable phenomena were rarely recognized by these students (Van Driel & Verloop 2002).

In the science field of physics, the core of modelling is making approximations. This comes up regularly in lessons about gravitational fields. For example, a statement such as "in this problem you can neglect the air resistance" presents an approximation of the conditions that would actually exist. The use of models can take into account such approximations when attempting to solve complex problems such as those involving systems building on knowledge from different technological fields to understand and analyze each part of a system, how that part works, and how it interacts with other parts. This method of examining and solving a problem also presents the opportunity to take into account the relationships between other business areas, such as finance, sales or stakeholders, in order to efficiently understand and manage the entire system throughout the product lifecycle.

Modelling in Engineering

Using and creating simplified representations of reality is a fundamental aspect of modelling in general. Students learning to model often use a variety of representations to express, test, revise, and interact with their own thinking. Accordingly, the construction of models often depends on the fluency of the representation and the ability to translate between and within different kinds of representation (Moore et al 2013).

Modelling in engineering takes on additional specific characteristics, often requiring a high degree of precision and accuracy, as they are used to predict the behavior of complex systems (Lammi, et al., 2020) under various conditions. These models must account for practical constraints such as material properties, safety factors, and regulatory standards. Moreover, engineering models are frequently used to optimize designs, ensuring that solutions are both feasible and efficient. This practical application necessitates a thorough understanding of the underlying physical principles and the ability to apply these principles in a variety of real-world scenarios.

The role of models and modelling in secondary technology and engineering education is crucial for helping students grasp the complexity of technological systems. Their role emphasizes that student engagement with models in engineering is essential for developing the skills needed to manage real-world design challenges, where precision, feasibility, and efficiency are key considerations (Norström & Hallström, 2023). By distinguishing these aspects, it becomes clear how the general principles of modelling are applied and expanded within the field of engineering. While models are used across the fields of both technology and engineering, engineering is a specialized field within technology that focuses on the development and optimization of systems and solutions. In engineering, models are designed to predict systems behavior under specific conditions, ensuring precision and functionality in practical applications. This professional focus on development and optimization requires the use of models that are both precise and quantitative in guiding the creation of real-world solutions.

Given the integral role of modelling in the fields of both science and technology and engineering, there is a growing need to create teaching materials that emphasize the core objectives of technological literacy. Modelling is an essential component of this literacy, and it must be framed in a way that highlights its importance in both the conceptualization and development processes within technology and engineering contexts (Norström & Hallström, 2023). Previous studies have also emphasized the critical role of models in these contexts, including foundational work by Gilbert et al. (2000), France, Compton, and Gilbert (2011), Haglund and Strömdahl (2012), and Nia and de Vries (2017). These studies offer key insights into the use of models for enhancing understanding in both technology and engineering education, underscoring the need for continued focus on this area in educational research.

Conceptual Distinction Between Scientific and Technological Models

Although modelling is central in both science and engineering, scientific and technological models differ in epistemological orientation and educational function. In science education, models are typically used to explain, predict, and represent natural phenomena and are often evaluated in terms of explanatory coherence and predictive adequacy (e.g., Gilbert, 2004; Grosslight et al., 1991). In contrast, technological models are embedded in design-oriented practices: they are used not only to represent existing systems, but also to guide the development, optimization, and realization of artefacts and technological systems under practical constraints (e.g., France, Compton, & Gilbert, 2011; Nia & de Vries, 2017; Wells, 2021). This distinction is pedagogically important. Students may encounter scientific models primarily as explanatory representations, whereas technological models may appear as drawings, schematics, prototypes, simulations, process models, and planning artefacts that support design decisions and production processes. Because technological models can have both representational and operational functions, students may hold a narrower *product-like* view of models and may fail to recognize abstract representations (e.g., equations, processes, schedules) as models within engineering contexts.

In this study, to clearly distinguish technological models from scientific models, we define a technological model as a representation (physical, graphical, symbolic, or procedural) that is purposefully constructed to support the analysis, design, prediction, optimization, or communication of a technological system and/or artefact. This definition aligns with accounts of models in technology and engineering education that emphasize their dual nature as both representational and action-guiding artefacts (Wells, 2016; Nia & de Vries, 2017).

Research Problem

Modelling is widely recognized as a central epistemic practice in both science and engineering (NGSS Lead States, 2013; Ford, 2015; Schwarz et al., 2022; Yesilyurt et al., 2024). Contemporary research emphasizes that modelling involves explanation, prediction, and design-oriented reasoning rather than merely the use of representations (Schwarz et al., 2017; Hallström & Schönborn, 2019). In engineering contexts specifically, models function as tools for iterative design, optimization, and decision-making, which differentiates them from purely explanatory scientific models. However, the extent to which modelling is explicitly taught as a structured and reflective practice varies across subjects and educational contexts. Although models are frequently used in classrooms, explicit attention to the epistemological and methodological dimensions of modelling remains uneven in secondary education (Svoboda & Passmore, 2013). This suggests that the didactic knowledge required of educators to support modelling as a core practice continues to develop. However, to date,

comparatively few empirical studies have explicitly examined students' conceptions of technological models in engineering and technology education, although interest in this area has increased in recent years (e.g., Nia & de Vries, 2017).

Research Goals

The main goal of our research was to identify the conceptions upper secondary students hold regarding technological models, building on our investigation of their preconceptions. In addition to understanding their existing perceptions, we sought to explore which factors influence the development of these concepts over time. The secondary goal is to continue developing comprehensive insights into conceptual understandings of technological models held by students before introducing these concepts into the curriculum. By examining background variables such as gender, language group, and the presence of Science, Technology, Engineering, and Mathematics (STEM) subjects in the curriculum, we aimed to uncover how these factors contribute to shaping the conceptions of technological models held by students.

Method

Research Design

This study is grounded in a pragmatic mixed-method orientation. Ontologically, we treat students' conceptions of technological models as context-dependent understandings that are shaped by educational experiences and language/curricular contexts. Epistemologically, the qualitative component adopts an interpretivist stance aimed at reconstructing how students articulate and explain their conceptions. Conversely, the quantitative component adopts a post-positivist stance aimed at identifying patterns and associations within student responses across subgroups. The overall theoretical lens is conceptual change and modelling-as-practice, which guided the development of the qualitative prompt, the construction of questionnaire items, and the integration (triangulation) of qualitative themes with quantitative factors. The study followed an exploratory sequential structure: the qualitative component was conducted and analyzed first and informed the construction of the questionnaire, after which the quantitative component was administered to a larger sample and the two strands were integrated through triangulation.

Participants

To investigate the conception of technological models held by students, the upper secondary school technology and engineering program was deemed a logical starting point as they require more knowledge of scientific concepts, principles, and mathematics than what students obtain throughout their lower secondary school education. A total of 345 students took part in the research, all

of whom were in the first year of upper secondary education (approximately 15-16 years old), which corresponds to the beginning of pre-university specialization within the European school system (Baird et al., 2017). Of these, 72 students (36 girls and 36 boys) participated in the qualitative component of the study by writing essays and taking part in interviews, and 338 students (155 girls and 183 boys) completed the questionnaire; 65 students participated in both components. To be consistent with previous studies conducted by the authors having an international focus (Köycü & de Vries, 2016), this study was also international based on the participant population, allowing for a more comprehensive insight into student understandings of technological models.

Data Collection

Qualitative

The goal of the exploratory qualitative component of the study was to gain a deeper understanding of how students conceptualize technological models through analysis of written essays and responses during semi-structured interviews. In both cases the same open-ended question (What do you think a technological model entails?) was posed to explore student conceptions of technological models. Essay and interview responses were collected simultaneously, and within the same instructional period to ensure student conceptions were captured within a consistent contextual frame. Written essays were completed individually by the 72 participating students (36 girls and 36 boys) during regular class time under teacher supervision. Semi-structured interviews were subsequently conducted with all 72 of these students to clarify and deepen interpretations emerging from the written responses. The gender balance of this group was deliberately chosen to allow the qualitative data to reflect the views of girls and boys equally.

All data collection was conducted by the first author in collaboration with the classroom teacher to ensure procedural consistency. Interviews followed a predefined protocol to enhance reliability, and student responses were audio-recorded and transcribed verbatim. The written responses were collected in digital form. To ensure fidelity of implementation, all students received identical instructions, and no evaluative feedback was provided during data collection to avoid influencing responses.

The use of both written responses and interviews allowed for methodological triangulation. Written essays enabled students to articulate their individual conceptions independently, while interviews provided opportunities to clarify meanings, probe ambiguities, and explore underlying reasoning in greater depth. Combining both methods strengthened the validity of the qualitative findings.

Quantitative

To investigate the students' understanding of technological models quantitatively, we developed a questionnaire designed to assess the extent to which student perceptions aligned with the concept of a technological model as presented in the statements provided. The questionnaire was comprised of 30 True/False statements, asking students to determine whether each provided item (a picture) corresponded to their concept of a technological model.

The use of a binary (True/False) format allowed for clear categorization of responses and facilitated factor analysis; however, it also limits the degree to which nuanced understanding or uncertainty can be captured. Students were required to make a categorical judgment, which may have oversimplified more complex or tentative conceptions of technological models. Future research could benefit from incorporating Likert-scale items or open-ended follow-up questions to allow for more differentiated expressions of understanding.

We developed these thirty items based on the essays and interviews obtained in the qualitative part of this study, as well as insights from previous research on models, particularly in the fields of both science and engineering. To strengthen content validity, the items were reviewed by two colleagues with expertise in technology and engineering education prior to administration. Minor wording adjustments were made to ensure clarity and conceptual alignment. While much of the foundational research on models has been conducted in science, where models function primarily as tools for representation and explanation, it is important to acknowledge that models in engineering often differ in their focus. Engineering models are typically more precise and quantitative, designed to predict system behavior and guide practical applications.

By integrating insights from both fields, we aim to provide a more comprehensive understanding of how models can be used effectively in various educational contexts. The inclusion of items related to process models stemmed from the desire to investigate whether students perceive various types of models, including process models, as examples of technological models. The items (pictures) were presented, and the students had to indicate whether the pictured object was an example of a technological model. The use of pictures was considered necessary because the study aimed to examine students' spontaneous recognition of technological models based on visual representations rather than on abstract verbal definitions. Visual stimuli enabled students to respond to representations commonly encountered in technological and educational contexts.

The selected images were deliberately chosen to represent a range of model types, including scale models, schematic diagrams, symbolic representations (e.g., equations), process models, and representations of final products. The selection was informed by literature on modelling in science and engineering education (e.g., Gilbert et al., 2000; Nia & de Vries, 2017) to ensure conceptual

diversity and alignment with established categories of models. Moreover, because we were interested in investigating differences between ideas of subgroups of students, we added some background variables that proved to be important in a previous study that dealt with the overall concept of engineering (Köycü & de Vries, 2016). For this study, we selected gender, language group (groups of students in two international schools divided by their primary language) and the presence of a school subject on engineering in their curriculum. We aimed to find out whether these background variables have an influence on the choices students make about what would be a technological model, or would not. The questionnaire was administered electronically over a five-month period, with students requiring approximately 10 minutes to complete. The following is a list of example model items:

- *A model airplane*
- *A Kirchhoff circuit*
- *A physics formula*
- *A graph*
- *A three-dimensional plan of a house*

Each item was displayed separately, and respondents could indicate with *True* if they thought it was a technological model and with *False* if they thought it was not a technological model. Additionally, we included questions probing the functions of models and requested explanations to gain insight into how students perceive the purpose and utility of technological models. These questions aimed to provide a comprehensive understanding of student perceptions and interpretations of technological models, including insights into their conceptualization, functions, and practical applications.

The questionnaire was administered to students enrolled in two international schools located in Luxembourg. These schools were selected through pragmatic access within an existing professional network, a form of convenience sampling commonly applied in educational research (Cohen, Manion, & Morrison, 2018). At the same time, the international and multilingual structure of the schools provided access to a culturally diverse yet institutionally comparable student population.

We acknowledge that this sampling strategy limits the generalizability of the findings. And therefore, although the schools operate within harmonized curricular frameworks, differences in prior exposure to engineering concepts and cultural attitudes toward technology may have had an influence on student responses. The findings should therefore be interpreted as context-bound rather than universally generalizable.

The decision to conduct the research electronically was made to streamline data collection and processing, which has been shown to reduce costs and minimize data entry errors (Wright, 2005). By utilizing electronic platforms, such as online surveys or data collection software, the questionnaire could be

easily distributed to a large number of participants while maintaining data integrity (Dillman, Smyth, & Christian, 2014).

With the assistance of colleague teachers from the participating language sections, the questionnaire was administered to 338 secondary school students (155 girls and 183 boys), 65 of whom had also taken part in the earlier qualitative component. Table 1 shows the number of participants per language group. The data collected included not only responses to the questionnaire items but also background variables such as gender, language group, and the presence of STEM subjects in the curriculum. These variables were included to explore potential correlations between students' understanding of technological models and their demographic or educational characteristics (Bryman, 2016).

Table 1

Participants per Language Groupings

Participants	
Language	***n***
Bulgarian	6
German	42
English	37
Spanish	48
Estonian	3
Finnish	16
French	70
Latvian	4
Lithuanian	5
Dutch	29
Polish	22
Portuguese	29
Swedish	27
Total	338

Data Analysis and Results

In this section, the results of the qualitative component and of the quantitative component are presented separately, followed by the triangulation of the two strands. The qualitative component comprised essays written by, and interviews conducted with, 72 students (36 girls and 36 boys). The quantitative component comprised questionnaire responses from 338 students (155 girls and 183 boys), 65 of whom had also participated in the qualitative component.

Qualitative Analysis and Results

Participants and Procedure

The essays written by participants were not regular classroom assignments but were specifically designed as research instruments for this study. A total of 72 students (36 girls and 36 boys) responded to an open-ended prompt about their understanding of technological models during scheduled class time, and all 72 students subsequently took part in a semi-structured interview. All participants were informed that their responses would be used for research purposes, participation was voluntary, and anonymity was ensured.

Analysis Procedure

The essays were analyzed using qualitative content analysis rather than documentary analysis of pre-existing classroom artefacts, as the texts were generated specifically for data collection within this research project. To identify key themes and keywords through content analysis of essay and interview responses, we used IBM SPSS Text Analytics and NVivo. This approach allowed us to develop a more comprehensive understanding of the students' ideas regarding technological models through both written and spoken responses. Through thematic analysis, each essay was carefully examined to identify passages or sections that addressed the concept of technological models. These relevant passages were then coded, assigning labels or categories to represent the underlying meanings or ideas conveyed. The coding process involved systematically organizing the coded passages into broader categories or themes based on similarities in meaning or content. The process of analysis was conducted as follows:

1. Data Coding: Essays were imported into NVivo, where text segments related to model descriptions were systematically coded. This involved identifying and labeling excerpts where students discussed different types of models.
2. Category Formation: Using NVivo's coding framework, we grouped these codes into broader categories based on common themes and characteristics identified in the students' descriptions. The four main categories emerged as: Schematic Representation Concept, Scale Model Concept, Number Sequences and Graphs Concept, and Functional Representation Concept.
3. Categorization and Analysis: Each category was further refined by reviewing the coded data for consistency and relevance. NVivo's querying tools were used to examine patterns and frequencies within each category, ensuring that the categorization reflected the students' conceptual understanding accurately.
4. Validation: To ensure robustness, the categorization was cross-checked by three colleagues. Any discrepancies in coding or categorization were discussed and resolved to achieve consensus.

Keywords and Concept Categories

The keywords identified through the qualitative content analysis process provide insights into the breadth and depth of students' understanding of technological models. Table 2 presents the keywords identified in the students' essays and interviews, grouped by the four concept categories that were subsequently derived from them.

Table 2

Keywords identified in students' essays and interviews, grouped by concept category

Concept Categories			
Schematic Representation	Scale Model	Number Sequences and Graphs	Functional Representation
map	mini car	source code	Kirchhoff circuit
floor plan	model plane	graph of movement	physics equation
2D model	prototype	graph of nuclear decay	applet
atom model	3D model of a house	graph of Ohms law	production process

Note. In addition to the keywords listed above, more general modelling terms such as scheme and representation, as well as keywords including reaction formulas, AutoCAD drawing, miniature, flowchart, production schedule, and simulation, occurred in the students' responses.

These keywords encompass a range of representations and applications of technological models as articulated by the students. While some keywords, such as schemes and representation, capture more general concepts related to modelling, others, like scale model and reaction formulas, represent specific types or forms of technological models. The keywords listed in Table 2 are not exhaustive but rather indicative of the diversity of ideas expressed by the students. The inclusion of both general and specific keywords reflects the multifaceted nature of technological models as perceived by the students. For example, the presence of keywords like floor plan and AutoCAD drawing highlights the students' recognition of various visualization techniques used in modeling, while terms like prototype and reaction formulas underscore their understanding of modelling in practical and theoretical contexts, respectively. By providing this overview of the keywords identified in the qualitative analysis (Table 2), we aim to offer a nuanced understanding of students' perceptions and conceptions of technological models as revealed through their essays. By comparing all the keywords in the essays, we were able to derive main categories of keywords. Of course, this method of coding is never entirely independent of existing ideas about technological models under study.

The following four categories emerged from the qualitative analysis. Although the categories were derived inductively from students' responses, their interpretation was informed by established distinctions in modelling literature, particularly between representational, symbolic, procedural, and design-oriented models (Gilbert et al., 2000; Hallström & Schönborn, 2019). The categories therefore reflect both empirical clustering in the data and alignment with existing theoretical perspectives.

1. Schematic Representation Concept: Includes models used as schematic representations of objects or ideas, such as maps, floor plans, and 2D models. These models provide an abstract representation of reality, as described by students in their essays.
2. Scale Model Concept: Encompasses physical or virtual scale models of objects or systems, including mini cars, model planes, and 3D models of houses. These models serve as simplified or scaled representations, reflecting their descriptive use by students.
3. Number Sequences and Graphs Concept: Includes models that use mathematical or graphical representations, such as graphs of movement, graphs of nuclear decay, and mathematical equations. Students' descriptions highlighted these models' roles in illustrating numerical data and trends.
4. Functional Representation Concept: Comprises models representing functional aspects of systems or processes, such as source code, applets, and production processes. These models focus on the operational or symbolic aspects of systems, as described in the students' essays.

The use of NVivo facilitated a structured and detailed analysis of the essays, enabling us to identify and categorize the conceptualizations of models effectively. This approach provides insights into students' understanding of technological and mathematical representations and serves as a foundation for evaluating their comprehension of these concepts. However, technological and non-technological models were often mixed in students' descriptions, indicating that they struggled to distinguish between the two. This suggests that students do not consistently distinguish between models used within technological design contexts and models originating from scientific or mathematical domains. In this study, a technological model is defined not by its form (e.g., diagram, equation, or scale model), but by its functional role within processes of technological analysis, design, optimization, or decision-making. From this perspective, certain models may function as *loan-models* when concepts or representations from science or mathematics are appropriated for technological purposes. The distinction therefore lies not in the disciplinary origin of a model, but in its intended use within technological practice. Addressing this confusion is essential to help students develop a clearer understanding of the role and nature of technological models in engineering contexts.

Student Recognition of Model Types

The recognition of models as schematic representations of reality among students was evident from the study's outcomes. Specifically, a substantial proportion of students identified 2-D models, 3-D models, Kirchhoff circuits, and miniatures as technological models. This recognition suggests that students may perceive these models as abstractions or simplifications of real-world systems or objects. This interpretation is supported by students' written explanations, in which they frequently referred to models as copies, scaled versions, or representations of something that already exists. Such descriptions indicate a representational rather than a functional or design-oriented understanding of models. To elaborate, a model, in the context of engineering education, serves as a simplified representation of a more complex reality. For example, a 2-D model might depict a cross-sectional view of an object, while a 3-D model provides a spatial representation. Kirchhoff circuits illustrate electrical principles through schematic diagrams that abstract the real-world behavior of electrical systems. Miniatures, on the other hand, offer scaled-down representations of objects or systems, making complex structures more comprehensible. The ability of students to classify these various forms of models as technological representations indicates an understanding that these models, despite their simplifications, capture essential features of the systems they represent. This understanding aligns with the concept of models as tools for bridging the gap between theoretical concepts and practical applications. In their essays and interviews, students also mentioned real products among their examples of models (*I see real products as models we can analyze.*).

However, it is important to note that while students were able to categorize these models, the depth of their understanding regarding the schematic nature of these models may vary. Further analysis is needed to assess whether students truly grasp the concept of models as abstractions or if they recognize them merely as physical or visual representations. This distinction is crucial for ensuring that students not only identify models but also comprehend their role in representing and simplifying complex systems.

In contrast, the study revealed that models representing processes, mathematical statements or equations, and production schedules were not consistently recognized as models by the students. This observation is primarily based on the absence of these types of models in the students' responses when asked to identify examples of technological models. For instance, models such as flowcharts, production schedules, equations used to represent engineering principles, and symbolic diagrams were notably missing from their responses. One student remarked during an interview, *I thought a model was something physical, like a diagram or a small machine. I didn't realize equations could be models.* Another said, *I know about formulas in math, but I never thought of them as models, just calculations*. This omission suggests a gap in students' recognition of these types of models as valid representations within engineering contexts. Examples of such abstract models can be found in equations representing physical laws, such as Newton's general gravitational force formula in physics or the reaction equation of decomposing water into its components in chemistry, and in production schedules that optimize manufacturing processes.

These observations were further substantiated by two additional qualitative data sources, namely the semi-structured interviews conducted with the 72 essay writers and the open-ended explanation questions embedded in the questionnaire. These data were therefore not collected separately from the procedures already described but constitute the interview and open-response components of those same procedures. Together, these sources revealed that students often struggled to articulate how abstract models like equations, process diagrams, or production schedules fit into their understanding of technological models. For example, when presented with an exploded view or a symbolic equation during the interviews, students frequently failed to classify these as models, indicating a limited recognition of their role in representing engineering concepts. One interviewee stated, *I never thought of a production schedule as a model, it's more like a plan*. On exploded views, one student explained, *Exploded views show how things fit together, but I didn't think of it as a model*. Interestingly, number sequences, graphs, and simulations were occasionally recognized as models; as one student put it, *Graphics and simulations can be models, I think*.

This evidence points to a broader issue: while students may recognize and understand visual or physical models such as scale models or 3D drawings

(*Models are like smaller versions of real things*; *Drawings are models because they show how things look or work*), they may not fully appreciate or identify the importance of models that abstract or symbolize complex processes or mathematical relationships (*Equations are more like calculations, not models*; *I never thought of processes as models, just steps*). Kirchhoff circuits formed a clear exception among the more schematic representations (*I learned about these in physics class, they are definitely models*). Addressing this gap in recognition is crucial for ensuring that students develop a comprehensive understanding of all types of models used in engineering. Table 3 summarizes the extent to which the different model types were recognized by students in the qualitative data.

Table 3

Student Model Type Recognition

Model Type	Recognition	Sample Student Quotes
Real Products	Yes	*I see real products as models we can analyze.*
Scale Models	Yes	*Models are like smaller versions of real things.*
2D and 3D Drawings	Yes	*Drawings are models because they show how things look or work.*
Kirchhoff Circuits	Yes	*I learned about these in physics class, they are definitely models.*
Exploded Views	Sometimes	*Exploded views show how things fit together, but I didn't think of it as a model.*
Equations	No	*Equations are more like calculations, not models.*
Production Schedules	No	*I don't see a production schedule as a model, it's more of a plan.*
Processes	No	*I never thought of processes as models, just steps.*
Graphics and Simulations	Sometimes	*Graphics and simulations can be models, I think.*

Note. In the questionnaire, real products were generally not classified as technological models (Table 4); this divergence between the two data sources is addressed in Triangulation Section.

Quantitative Analysis and Results

Participants and Analytical Procedure

The questionnaire was completed by 338 students (155 girls and 183 boys), 65 of whom had also participated in the qualitative component. In all language groups (Table 1), the questionnaire was written in English, as the students had at least C1 proficiency in that language. Furthermore, the use of pictures helped prevent validity issues related to language differences (Reeves & Hedberg, 2003).

Although the questionnaire was administered electronically in English and students were expected to have at least C1 proficiency, linguistic and cultural differences may still have influenced interpretation. To mitigate potential misunderstandings, visual representations accompanied each item, and qualitative responses were analyzed with attention to contextual meaning rather than literal phrasing. Nevertheless, subtle differences in how students from different language backgrounds interpreted terms such as model cannot be entirely excluded. This represents a limitation of the study and should be considered when interpreting cross-group comparisons.

Upon data collection, rigorous analysis procedures were employed using the statistical software SPSS. Descriptive statistics, including measures of central tendency and variability, were computed to summarize the dataset (Field, 2013). This allowed for a comprehensive overview of students' responses to the questionnaire items and their demographic profiles. Furthermore, inferential statistical techniques (analysis of variance and independent-samples *t*-tests) were applied to examine whether students' conceptions of technological models differed according to background characteristics such as language group, gender, or the presence of STEM subjects in their curriculum (Tabachnick & Fidell, 2019).

In terms of research ethics, all participants were informed about the purpose of the study, and their participation was entirely voluntary. Consent was obtained prior to data collection, and the confidentiality of the students' responses was ensured throughout the process. The use of anonymous electronic surveys further safeguarded the privacy of participants, and no personal identifying information was collected.

Dimensions of Students' Concepts of Technological Models

To analyze the students' responses to the questionnaire, we conducted an exploratory factor analysis on the quantitative data. This analysis aimed to identify underlying dimensions within student responses and to verify the presence of specific categories within the larger sample. Factors were retained based on eigenvalues greater than 1 and inspection of the scree plot. Items with factor loadings above 0.40 were considered meaningful contributors to a factor, while cross-loading items were examined for conceptual coherence before

retention or exclusion. Items were included in a factor when they demonstrated a substantial loading on that factor and conceptual coherence with the emerging construct; items with low loadings or cross-loadings were excluded from scale construction to maintain internal consistency and interpretability.

To construct scale scores from these factors, we selected items that were strongly associated with each factor, using the mean of these items. Items that scored lower on a factor were excluded until excluding them resulted in a significant decrease in Cronbach's Alpha. Cronbach's Alpha was used to evaluate the reliability of each scale, with a threshold of 0.65 considered acceptable for reliability (Nunnally & Bernstein, 1994). Statistical significance was determined using an alpha level of .05. Differences in categorical responses were analyzed using chi-square tests, and for comparisons involving factor scores, mean differences were evaluated and statistical significance was established when $p < .05$. Effect sizes were examined where appropriate to assess the practical relevance of statistically significant findings.

The results of the factor analysis are presented in Table 4. Ten scales were found with at least two items in the questionnaire. All scales had a reliability score above 0.68, indicating acceptable internal consistency for exploratory research, and almost three quarters of the variance was accounted for in the scales that emerged. Each scale represents a distinct concept or category of technological models derived from the data. The Cronbach's Alpha values presented in the second column of Table 4 indicate that all scales meet the reliability criterion when the 0.65 threshold is applied. This suggests that the identified scales provide a consistent measure of the students' perceptions of technological models.

Table 4

Categories of concepts of models in students' questionnaire with mean scores per scale and the corresponding standard deviation

Scales	α	*N*	% σ^2	Cumulative %	*M*	SD
Real products	0.897	4	12.439	12.439	0.11	0.05
Exploded views	0.928	2	10.209	22.648	0.20	0.07
2D drawings	0.879	4	9.672	32.320	0.62	0.11
Scale models	0.845	3	7.528	39.848	0.82	0.06
Equations	0.741	3	6.673	46.521	0.24	0.14
Kirchhoff Circuits	0.925	2	6.257	52.778	0.70	0.19
Production schedules	0.887	2	5.991	58.769	0.35	0.04
Processes	0.682	2	5.867	64.636	0.41	0.06
3D drawings	0.712	2	4.852	69.488	0.75	0.13
Graphics	0.766	3	3.507	72.996	0.59	0.12

To determine whether the scales made conceptual sense, the resulting item groupings were interpreted in light of the qualitative findings from the essay and interview data as well as existing literature on technological models; this comparison is presented in the triangulation section. For example, the following four images came together in the *real products* scale: a picture of a car, a child's dining chair, a picture of a house, and a motorbike. In this context, *real products* refer to tangible, concrete objects that students encounter in their daily lives, such as cars, planes, and household appliances. Although these items can technologically be considered models of design and engineering processes, students perceive them as finished, actual products rather than abstract representations or conceptual models. For the scale *exploded views*, the images of the exploded view of an alternator and an exploded view of a mobile phone came together.

Students' Judgements of the Model Categories

From Table 4, we can deduce that students generally speaking do not see real products as technological models. These responses indicate that students clearly distinguished between representations of objects and the objects themselves. Many students also indicated that *end products cannot be models* as an explanation for their choice in the survey. For exploded view items, the students also indicated that they did not see it as a technological model, but they did not give an unambiguous explanation. Students came up with various explanations; the explanation *Exploded view cannot be a model, because it is a finished product that has been taken apart* was given by a quarter of the students.

One of the most common arguments provided by the students was that a list of components is not considered a model. This was indicated by 38% of the students, the highest percentage for any scale, without further explanation. This lack of elaboration suggests that students found it difficult to articulate why they did not see a list of components as a model. A plausible interpretation is that students tend to associate models with visual or schematic representations that directly relate to the final product, whereas a list of components might be viewed more as a reference or inventory, rather than something that demonstrates the function or purpose of the end product. They seem to expect a model to have a visual or functional connection to a tangible outcome.

In contrast, students did view 2-D drawings as good examples of models, primarily because these were seen as accurate representations of what the final product would look like. This suggests that students primarily understand models as something that visually reflects the form or structure of an object. The notion of a model as a schematic or abstract representation of reality, for them, seems to apply mainly when the model closely resembles the actual object in a visual sense.

However, formulas were not seen as appropriate examples of technological models. According to the students, formulas did not allow them to *directly see the function of the end product*. This reflects a broader difficulty students face in connecting abstract mathematical representations to real-world objects or outcomes. For these students, models need to be something concrete and immediately recognizable as related to a physical or functional product. They struggle to conceptualize formulas as models because they do not offer a direct, visual pathway to understanding what the final product might look like or how it might function.

Another key finding was that many students believed a model should always serve as a preliminary stage in the development of a final product. This belief is reflected in statements such as, *It does not show what it is intended for and does not give an image of a final product*. This suggests that students primarily see models as tools that guide the production process and not as independent representations of systems or phenomena. They seem to feel that a

model must provide clear insights into the practical outcomes of a project, rather than simply representing the relationships or processes at play.

On the other hand, Kirchhoff circuits were considered by students to be good examples of models because they clearly illustrated how the current flows and where the potential differences occurred. A significant proportion of the students noted that *Kirchhoff circuits are models because it is a sketch with all the parts on it: the battery is known, the direction of the current is known, the voltage is known, and even the devices in the circuit are known. A sketch can be a model*. This response indicates that students regard schematic representations, where the relationships between components are clearly visible, as models. The ability to visualize the flow of current and the distribution of voltage helps students perceive the Kirchhoff circuit as a valuable model for predicting and understanding the behavior of the system.

Production schedules and processes, however, were not seen as suitable examples of technological models. Students reported that these did not provide much insight into *predictions about an end product or end result*. This again reinforces the idea that students place high value on models that offer a direct visual or functional connection to a final product. They seem to feel that models should offer predictive power about how something will function or appear in its final form, and production processes or schedules do not meet this expectation.

Scale models and 3D drawings were widely viewed by students as excellent examples of technological models because they were *very accurate representations of reality* and one could *clearly see the functions of the end product*. This highlights the students' focus on the visual fidelity of a model as a key determinant of its value. Models that closely resemble the actual product in terms of form and function were seen as the most useful and accurate representations.

Graphs were also regarded as good examples of technological models, as they allowed students to *understand the effects of different factors on the quantity under investigation*. This indicates that while students place significant emphasis on visual representation, they are also capable of appreciating graphical models that help them conceptualize relationships between variables, especially in quantitative terms. Graphs, while abstract in nature, were nonetheless valued for their ability to visually demonstrate how changes in one factor could influence another.

These findings suggest that students' conceptions of technological models are heavily influenced by the models' visual and functional resemblance to the final product. They appear to struggle with more abstract forms of representation, such as formulas or production processes, which do not provide an immediate or tangible connection to the end result. For students, a model is most effective when it not only represents but also visually communicates the key features and functions of the product or system it is modelling.

Differences Between Subgroups

The number of students per language group allowed us to verify whether a language group as a background variable has a significant influence on students' perception of technological models. We hypothesize that language and cultural differences may impact students' understanding and interpretation of technological concepts. For example, students from different language backgrounds may have varying levels of exposure to technology-related terminology or different educational experiences that shape their conceptualizations of technological models. Additionally, cultural factors such as attitudes towards technology or problem-solving approaches may influence how students perceive and interact with technological models. Previous studies on engineering attitudes and perceptions have indicated that country of origin was a significant background variable that yielded differences (Jiang et al., 2023; Köycü & de Vries, 2016). Given such findings, it is plausible to expect that similar cultural and contextual factors, reflected in language groups, could influence students' perceptions of technological models. Although there are several groups represented by only a few participants, such as the Bulgarian, Estonian, Latvian, and Lithuanian groups, there are ample groups of adequate size to ensure a robust analysis.

We conducted an ANOVA test to determine whether the language section in which a student is situated influences their conceptions of models. If the significance level (*p*-value) is below 0.05, this would indicate a statistically significant difference between groups based on language section. However, as shown in Table 5, none of the ten scales showed a statistically significant difference; the language section appears to have no influence on any of the scales. The table is included to provide transparency and to document the absence of language-based effects in the dataset.

Table 5

ANOVA Results: Language Section (No Statistically Significant Differences)

Scales	Sig. (*p*-value)
Final products	> 0.05
Exploded view	> 0.05
2D drawings	> 0.05
Scale models	> 0.05
Equations	> 0.05
Kirchhoff Circuits	> 0.05
Production schedules	> 0.05
Processes	> 0.05
3D drawings	> 0.05
Graphics	> 0.05

Following the conduct of the ANOVA, we performed an independent samples 2-tailed *t*-test to investigate whether gender influences students' conceptions, as shown in Table 6. The two-tailed *p*-values for all scales were greater than 0.05, indicating there were no statistically significant differences based on gender across any of the scales. From these analyses, it is evident that neither the language section nor gender yielded statistically significant differences in the conceptions of technological models held by students.

Table 6

Independent Samples Test for Gender

Scales	Sig. (2-tailed) *p*-value
Final products	0.991
Exploded view	0.210
2D drawings	0.748
Scale models	0.482
Equations	0.841
Kirchhoff Circuits	0.441
Production schedules	0.236
Processes	0.897
3D drawings	0.817
Graphics	0.918

With an independent samples *t*-test we investigated whether the background variable of following a STEM course has an influence on the factors found (Table 7). If the significance is lower than 0.05 for a *t*-test, this indicated there was no statistically significant difference in student choices based on a given background variable.

Table 7

Independent Samples Test Following a STEM Course

Scales	Sig. (2-tailed) *p*-value
Final products	.310
Exploded view	.045
2D drawings	.025
Scale models	< .001
Equations	.945
Kirchhoff Circuits	.028
Production schedules	.002
Processes	.675
3D drawings	.003
Graphics	< .001

Results of independent samples *t*-tests revealed statistically significant differences on seven of the ten scales based on students' prior engagement in a STEM subject. The students who took a STEM subject more often called the exploded view an example of a technological model compared to students who do not take a STEM subject. Apparently, engagement in a STEM subject leads to a better image of models in relation to the exploded view scale. With regard to the 2D drawings scale, there was again a statistically significant difference, in that students having previously engaged in a STEM subject saw this scale more clearly as a model than students with no prior engagement in a STEM subject. Scale models were much more often seen as no technological models by students having no prior engagement in a STEM subject than by the other group of students. We can say that for these three scales, where engagement in a STEM subject had an influence on the students' perception, this influence was positive.

However, the answers of the students who did not engage in a STEM subject were better for the Kirchhoff circuits and Production schedules scales than the students with a subject. Apparently, engagement in the STEM subject as it is currently taught gives a misconception with regard to the model function of the circuits and schedules. Because the present design is not causal, this reverse pattern cannot be explained with certainty; one tentative possibility is that the more theoretical treatment of circuits and schedules in STEM subjects draws attention away from their schematic model function, but this would need to be tested directly in future research.

For the scale '3D drawings', the STEM subject students were more often correct and saw the 3D drawings as a technological model. Graphs were also more often seen as a technological model by students with a STEM subject. Also, for these scales, the school subject appears to have a positive influence with regard to the model concept. A likely reason why STEM students performed better on the *3D drawings* and *Graphs* scales could be that these types of models are more directly integrated into STEM curricula. STEM subjects often emphasize spatial reasoning and visual representation, which are key components in understanding 3D models and graphs. In many STEM courses, students regularly encounter 3D models in fields like engineering, physics, and architecture, where these models are used to visualize complex structures and systems. Similarly, graphs are fundamental tools in subjects like mathematics and science for analyzing data and understanding relationships between variables. Therefore, the better performance of STEM students on these scales can be attributed to the fact that these types of models are more explicitly taught and used as learning tools in STEM education, reinforcing their understanding of these models as technological representations. This suggests that the STEM curriculum is effective in conveying the model function of 3D drawings and graphs.

Triangulation of the Qualitative and Quantitative Findings

The study followed an exploratory sequential logic in which the qualitative strand informed the construction of the quantitative instrument, after which the two strands were compared. The qualitative themes derived from the essay analysis were not imposed a priori on the factor analysis but were compared retrospectively with the quantitative factors. This allowed for analytical triangulation, examining whether patterns emerging from students' open-ended descriptions were reflected in their categorical questionnaire responses. In this comparison, attention was paid to whether the findings of the two strands converged, complemented one another, or diverged. Where alignment occurred, this strengthened construct validity; where discrepancies appeared, these were interpreted as indications of conceptual ambiguity rather than forced convergence.

The factors identified through the factor analysis align closely with the categories derived from the students' essays. This consistency is evident in several ways:

1. Category Alignment: The factors revealed by the factor analysis correspond to the categories observed in the essay analysis. For example, the factor related to *Schematic Representation* includes items such as maps and 2D models, which were also frequently mentioned in students' essays under the Schematic Representation Concept. This alignment confirms that the factor accurately reflects the conceptualization of schematic models.
2. High Correlation with Clear Interpretations: The items that exhibited the strongest correlations with each factor were those that provided clear and unambiguous representations of the factor's concept. For instance, the items correlating strongly with the *Scale Model* factor included mini cars and model planes, both of which were prominently featured in the essays as examples of scale models. This strong correlation underscores the factor's validity in representing scale models as described by students.
3. Examples of Consistency: (a) Schematic Representation Concept: Essays frequently cited maps and floor plans as examples of schematic representations, and factor analysis identified a factor where these items had high loadings, reinforcing the idea that students consistently view these models as schematic. (b) Number Sequences and Graphs Concept: Students' essays often included references to graphs and equations as tools for representing numerical data, and the factor analysis similarly identified a factor with strong correlations to these items, demonstrating consistency between essay content and factor identification. (c) Functional Representation Concept: Functional models such as source codes and production processes were mentioned in essays and also appeared as high-loading items in the corresponding factor, indicating that students' descriptions of functional models are accurately captured by this factor.

4. Validation through Item Correlation: The validity of the factors is further supported by the fact that the items with the highest correlations were those that allowed for a straightforward and accurate interpretation of the factors. For example, items like Kirchhoff circuits and physics equations, which were strongly associated with the 'Functional Representation' factor, clearly fit the concept of functional models as defined by the essays.

The strong alignment between the factor analysis results and the conceptual categories identified in the essay analysis supports the validity of the factors. This consistency indicates that the factors derived from the quantitative data reflect the conceptual understandings described by students in their essays. An important argument for validity is that the items that correlated most strongly with a factor in all cases allowed for a clear and unambiguous interpretation of the factor. The analysis thus revealed notable similarities between the content of students' essays and their responses to the digital questionnaire.
One notable divergence between the two strands concerned real products. In the essays and interviews, real products were mentioned among students' examples of models, whereas in the questionnaire students generally did not classify real products as technological models (Table 4). In line with the analytical approach described above, this divergence is interpreted as an indication of conceptual ambiguity in students' understanding of the boundary between a model and the object it represents, rather than as a contradiction between the two data sources.

Conclusions

The conclusions of this study are organized in relation to the main research goal (identifying the conceptions upper secondary students hold regarding technological models) and the secondary goal (exploring which factors may impart an influence on these conceptions).

Students' Conceptions of Technological Models

With regard to the main research goal, the findings show that upper secondary students possess a basic understanding of technological models, yet their conceptions remain strongly tied to visual resemblance and proximity to a final product. Students' ideas about the nature of a technological model, as found in this study, suggest that according to students a technological model should be a complex entity, where the representation of reality seems to be a prerequisite. This view was reflected in almost all of the students' essays, which included representations such as 2D drawings, scale models, and 3D diagrams. However, many students did not consider formulas, production schedules, or processes to be technological models, likely because they do not directly resemble the final product. This suggests that students' conceptions only partially align with the definition of technological models proposed, particularly with respect to their

functional, predictive, and design-oriented roles. From a conceptual perspective, the distinction students made between representations and the objects themselves is appropriate, as physical objects do not constitute models but may serve as referents for modelling activities.

Interestingly, there was no significant division in this study between students' views on technological models as schematic representations, scale models, number sequences, or graphs. What was clear from both the essays and the interview data is that students consistently viewed technological models as something directly related to the final product or outcome. The triangulation of the two strands confirmed this picture, showing notable similarities between the content of students' essays and their questionnaire responses. In contrast to previous studies among lower secondary school students, a distinct concept of a technological model was thus found among the upper secondary participants in this study.

Factors Influencing Students' Conceptions

With regard to the second research goal, no statistically significant differences were observed within the limits of this dataset with regard to language section (Table 5) or gender (Table 6). The absence of gender differences is particularly noteworthy because previous research at the lower secondary level has identified gender differences, but no such disparity was found here (Nia & de Vries, 2017).

Engagement in a STEM school subject, in contrast, was associated with statistically significant differences on seven of the ten scales (Table 7). For the exploded views, 2D drawings, scale models, 3D drawings, and graphics scales, students with a STEM subject responded more in line with the technological model concept, whereas for the Kirchhoff circuits and production schedules scales, students without a STEM subject gave answers that were more in line with that concept. Relatedly, for the half of the students for whom education in aspects of engineering is not part of their curriculum, representativeness was a greater requirement (84% of the essays) than for students who have a subject in which aspects of engineering are taught (48% of the essays). Although these differences are statistically significant, the magnitude of the observed differences should be interpreted with caution (Chittleborough et al., 2005; Nia & de Vries, 2017). In summary, the findings tentatively suggest that exposure to STEM subjects may be associated with differences in how students conceptualize technological models; however, no causal conclusions can be drawn from the present study.

Discussion

The discussion is organized around the implications of the findings. The findings are first interpreted in relation to prior research, after which implications for curriculum design and for teacher education, as well as

limitations and directions for future research, are discussed in separate sub-sections.

Interpretation in Relation to Prior Research

The strong association between technological models and visual resemblance to a final product aligns with earlier findings on students' conceptions of engineering (Köycü & de Vries, 2016) and parallels observations in science education research, where students often associate models with accurate visual representations (Gilbert et al., 2000; France, Compton, & Gilbert, 2011). Consistent with previous research on models in technology and engineering education (Nia & de Vries, 2017), students in this study tended to associate technological models with representations that directly communicate the characteristics of a final product, rather than with abstract or functional representations. This is a notable misconception that has been identified in other research as well (Gilbert et al., 2000), and it is consistent with Haglund and Strömdahl's (2012) findings, which highlighted students' preference for visual or tangible models over abstract representations like formulas.

Our results further indicate that secondary school students possess a more developed understanding of technological models compared to primary school students (Meredith et al., 2004). This progression is expected, given the age and educational differences, and suggests that secondary education provides a more solid foundation for students to engage with more complex technological activities. This developmental trajectory aligns with earlier research on the evolution of students' conceptualizations of models (Chittleborough et al., 2005) and supports the notion that educational progression contributes to a deeper understanding of both scientific and technological models. Previous studies, such as the one by Gilbert (1998), indicated that primary and secondary school students often perceive models in science as needing to be accurate representations of reality. Although these studies did not specifically address technological models, our findings suggest that a similar perception may extend to students' understanding of technological models as well.

This pattern may be understood in relation to students' prior learning experiences. In many school subjects, models are introduced primarily as visual or tangible representations (e.g., molecular models in chemistry or anatomical models in biology), which may reinforce the idea that resemblance to a final product is a defining characteristic of a model. Abstract or symbolic representations, such as equations, process diagrams, or production schedules, are often taught as computational or procedural tools rather than as models in their own right. As a result, students may not develop a broader understanding of models as functional representations that support analysis, prediction, and design decision-making. An interesting question, which begs for further investigation, is why students think that a technological model must directly

reflect the final product or outcome and cannot be a diagram, a process, or a formula.

Implications for Curriculum Design

From a pedagogical perspective, the findings suggest that technology and engineering education should explicitly address the multiple forms and purposes of models. Educational materials that provide balanced attention to all aspects of technological models may help improve students' overall perception and address the misconceptions found between students with and without engagement in STEM subjects. If future research confirms that exposure to STEM subjects is associated with broader understandings of technological models, curricula might consider more explicit integration of different model types (physical, schematic, symbolic, and procedural) within design-oriented activities. Instructional approaches could include comparing physical, schematic, symbolic, and procedural models of the same system, as well as making the role of models in design processes more explicit. Such strategies may help students move beyond a purely product-oriented view of models and develop a more integrated conceptual understanding. Our results suggest that future studies should also explore ways to teach students that technological models encompass a wider variety of representations, beyond just visual likenesses to reality. This highlights the importance of explicitly teaching the representational and functional nature of models in technological contexts.

Implications for Teacher Education

Beyond curriculum considerations, these findings underscore the importance of strengthening teacher education in technology and engineering. If teachers themselves predominantly conceptualize models as visual representations rather than as functional design tools, classroom practice may unintentionally reinforce a narrow understanding of modelling. Teacher preparation programs should therefore explicitly address the epistemological status of technological models and provide opportunities for prospective teachers to engage in modelling as an iterative and design-oriented practice. Professional development initiatives might include explicit strategies for discussing with students why equations, simulations, and process models also function as technological models. Making these distinctions explicit in classroom practice may help reduce the narrow, product-oriented view identified in this study and may help bridge the gap between students' representational conceptions and the broader functional roles of technological models.

Limitations and Future Research

Several limitations of the present study should be acknowledged. The schools were selected through convenience sampling; although the participants represented 13 language backgrounds (Table 1), they were drawn from only two

international schools in a single city, so the linguistic diversity of the sample should not be read as geographic or institutional representativeness, and the findings should be interpreted as context-bound rather than universally generalizable. The binary (True/False) format of the questionnaire limited the degree to which nuanced understanding or uncertainty could be captured, and subtle differences in how students from different language backgrounds interpreted terms such as model cannot be entirely excluded. Furthermore, perhaps the use of certain tools, such as molecular models in chemistry or anatomical models in biology, where representativeness is often part of the model, has influenced what students expect from a technological model; the present design cannot separate such prior experiences from the influence of the current curriculum.

These findings provide a basis for further investigation. Future research could explore these aspects in greater depth to better understand the nuances of students' perceptions and the potential impact of gender and educational background on their understanding of technological models. Incorporating Likert-scale items or open-ended follow-up questions could allow for more differentiated expressions of understanding, and longitudinal designs could examine how students' conceptions of technological models develop once these concepts are explicitly introduced in the engineering curriculum.

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Ethics Approval

This study was approved by Delft University of Technology

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Book Review

Teaching with AI: A Practical Guide to a New Era of Human Learning

Bowen, J. A., & Watson, C. E. (2024). *Teaching with AI: A practical guide to a new era of human learning*. Baltimore, MD: Johns Hopkins University Press. ISBN: 978-1-4214-4922-7, $24.95 (paperback), 280 pages

Consider a student who asks an artificial intelligence (AI) system for 10 ways to improve a water filtration prototype during a design challenge. The central question is not whether the student used AI. It is whether the student met the learning goal. Did the student compare trade-offs, revise criteria, test a stronger design, document decisions, and explain what human judgment added to their decision-making? *Teaching with AI* helps educators rethink how they teach, assess, and support student learning as generative AI becomes part of education. José Antonio Bowen and C. Edward Watson argue that AI is changing how people think, create, and work. Educators should respond by teaching students to use AI responsibly, critically, and productively.

Bowen and Watson are most effective when they translate broad concerns about AI into practical guidance on AI literacy, assignment design, assessment, feedback, and human judgment. Educators in Technology and Engineering Education can apply this guidance to design-based learning, systems thinking, iterative problem solving, and the responsible evaluation of emerging technologies. The book progresses from understanding AI to applying it in teaching and learning. Its instructional guidance is stronger than its treatment of ethical and systemic consequences.

One strength of the book is its approach to AI literacy. Bowen and Watson define it through tool selection, problem formation, prompt quality, verification, bias awareness, recognition of hallucinations, and iteration (pp. 42–61). Students must know when AI is useful, how to improve weak output, and how to judge whether a response is accurate, relevant, and appropriate. The authors support these skills by presenting task, format, voice, and context as features of an effective prompt and showing how refinement and iteration improve AI-generated responses.

Their approach to AI literacy transfers well to Technology and Engineering Education because it requires students to evaluate how inputs, constraints, assumptions, and system limitations shape AI-generated responses. Educators

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can apply the book's guidance to design briefs, system evaluations, fabrication tasks, and technical troubleshooting. Examples involving AlphaGo (pp. 67–68), AlphaFold (pp. 72–73), and AI-assisted design work at NASA (p. 39) show how AI can generate possibilities people may not consider. Humans remain responsible for selecting, testing, revising, and justifying those ideas.

Using AI to generate and critique ideas fits design-based learning because students retain responsibility for the design process. Students may use AI to generate alternatives or critique proposed solutions, but they must still frame the problem, test ideas, revise prototypes, and justify decisions with evidence. That benefit depends on how the activity is structured. Students who accept generated options too quickly may narrow their thinking or bypass their own problem framing. Teachers should structure AI use so students remain responsible for inquiry, testing, revision, and judgment.

Bowen and Watson provide their clearest guidance in the discussion of assessment redesign. They state that "all assignments are now AI assignments" (p. 198) and argue that new assignments should develop critical thinking and AI literacy. They also call on educators to define work that exceeds what AI can produce, assess how students complete it, and reconsider the importance of the final product (pp. 157–158). This shifts assessment from detecting AI use to examining students' reasoning, decisions, and evidence of learning.

Process-based assessment is especially relevant to Technology and Engineering Education. Design notebooks, sketches, prototypes, test data, troubleshooting logs, and revision records can help teachers determine what students learned and whether they met the learning goals. A finished product alone may not show how students tested ideas, revised their work, or used evidence to make decisions. Teacher educators in the field can use process-based assessment to help future teachers determine whether AI supported learning or replaced the thinking required by the assignment.

The book's instructional guidance is likely to remain useful even as many examples become dated. Bowen and Watson acknowledge that parts of the book could change before publication and explain that they reran prompts close to press time, often with newer AI versions (pp. 2, 6–7). That transparency helps readers separate lasting principles from temporary tool guidance. Examples involving specific tools, interfaces, and detection products will date more quickly.

The authors support their recommendations with empirical studies, reports, tool tests, student conversations, and practical experimentation. They identify prompts, responses, AI versions, and dates and acknowledge that their student conversations did not constitute a large statistical sample (pp. 3–7). Their transparency helps readers understand what the recommendations are based on and where the evidence is limited.

Bowen and Watson also offer useful guidance on AI detection and academic integrity. They explain that detection tools vary in accuracy, provide probability scores, and cannot prove that a student was deceitful regarding their use of AI (pp. 111–115). They urge educators to pair careful judgment with clearer policies and assignments that require evidence of student thinking rather than rely on detection tools alone (pp. 130–133). This guidance gives educators a practical response to suspected misuse.

The book's practical focus leaves less room for a sustained treatment of ethics and equity. Bowen and Watson acknowledge that they kept the discussion focused on practical concerns while arguing that AI ethics should be integrated into the curriculum (pp. 2–3). They address bias and hallucinations when explaining how AI systems work (pp. 17–19) and later discuss unequal access, privacy, detection, and false accusations (pp. 106–120). These topics receive less development than prompting, assessment, and assignment design.

The *Standards for Technological and Engineering Literacy* emphasizes the ability to evaluate the benefits, risks, trade-offs, access, control, and unintended consequences of technologies (International Technology and Engineering Educators Association [ITEEA], 2020). *Teaching with AI* focuses primarily on classroom practice rather than these broader questions. Technology and Engineering Education readers may therefore need additional resources to examine AI's benefits, risks, labor demands, environmental costs, and effects on human judgment.

Teaching with AI gives educators practical guidance for redesigning instruction and assessment in response to generative AI. Its strongest ideas transfer well to technology and engineering teaching, particularly in design-based learning, process-based assessment, and responsible AI use. Although the book does not fully address the broader social and technological consequences of AI, Bowen and Watson offer a useful guide that supports educators to adapt their instructional practice to prepare students to think, design, and learn alongside AI.

Adkinson, D. (2026). Book Review: *Teaching with AI: A practical guide to a new era of human learning*, *38*(1), 132-134.
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Miscellany

Scope of the *Journal of Technology Education*

The *Journal of Technology Education (JTE)* provides an international forum for scholarship on topics directly related to technology and engineering education, inclusive of the practices and designerly ways of knowing inherent to technological and engineering literacy. Manuscripts should focus on technology and engineering education research, philosophy, theory, or practice. In addition, the Journal publishes book reviews, editorials, guest articles, comprehensive literature reviews, and reactions to previously published articles.

Technology and Engineering Education (TEE) is a curricular program implemented at the PK-12 school levels for all students and at post-secondary institutions for those students interested in teaching or obtaining employment in technology or engineering fields. In some countries, states, and/or provinces TEE is a stand-alone program and in others it is part of broader programs in career and technical education (CTE) or vocational education and training (VET). At the PK-12 grade levels, the aim of TEE is for students to develop technological and engineering literacy, regardless of career aspirations. TEE students follow a minds-on/hands-on experiential approach to learning technology and engineering concepts. Within this approach students engage in the design of technological/engineering solutions while working under constraints and utilizing optimization and predictive analysis. Understanding that technology, the environment, the economy, and social systems are all interconnected is essential to being both informed citizens and knowledgeable users and designers of technology.

TEE curriculum is primarily taught at the PK-12 level by certified technology and engineering educators using design based learning to intentionally teach the inherent content and practices of science, technology, engineering, and mathematics (STEM) education. At the PK-5 grade levels, technology and engineering concepts and practices are often integrated into existing coursework, such as language arts, mathematics, science, and social studies. At the 6-12 grade levels, TEE programs typically consist of courses in (a) information and communication technologies, (b) technology and engineering design, (c) the built environment, (d) manufacturing, (e) energy, power, transportation, and logistics, (f) medical, agricultural, and biotechnologies, and (g) computation, automation, artificial intelligence, and robotics. Within these courses, students learn to apply core principles and practices of technology and engineering while refining their troubleshooting, research and development, design, and problem-solving skills. As such, the focus of TEE at the PK-12 levels is not on the preparation of future STEM

majors/students, but on providing an education that prepares all students to be technologically/engineering literate.

Editorial/Review Process

Manuscripts that appear in the Articles section have been subjected to a blind review by three or more members of the Editorial Review Board or other specialists in the field. This process generally takes two to three months, at which time authors are notified of the status of their manuscripts. Book reviews, editorials, and reactions are reviewed by the Editor.

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The manuscript submission process is facilitated by the University Libraries of Virginia Polytechnic Institute and State University. Authors should register, then submit manuscripts through the portal at https://jte-journal.org. Questions for the editors should be sent to: Editor, *Journal of Technology Education* at jte@iteea.org.

1. Manuscripts submitted must be original work, not previously published, not currently under consideration for publication elsewhere, approved by any/all co-authors, as well as approved tacitly or explicitly, by the responsible authorities.
2. Manuscripts submitted must be double-spaced Microsoft Word documents.
3. Manuscripts submitted must adhere to the guidelines published in the current *Publication Manual of the American Psychological Association* (e.g., 7th Edition), except that tables and figures should be embedded within the text rather than at the end of the document.
4. All figures, tables, line drawings, and graphs must be editable with Microsoft or Adobe products and in vector rather than raster format when possible. Shading should not be used as a background for illustrations or graphs and within bar graphs; if needed, fill patterns consisting of lines should be used. A high-resolution file for each figure should also be submitted with the manuscript. These should have a resolution of at least 300 dpi (600 dpi or above preferred) and be in JPG, TIFF, GIF, or PNG format.
5. Research manuscripts should generally be 22,000 to 40,000 characters in length, including spaces. They should include an abstract of up to 250 words and four to six key terms. Book reviews, editorials, and reactions should be approximately 6,000 to 12,000 characters in length.
6. Authors for whom English is not the primary language must enlist a native English editor for the manuscript prior to submission. The names and email addresses of the authors and the English editor must be identified on the title page of the manuscript.

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