Learning by Evaluating in Engineering Design Classrooms: A 5E Instructional Model Perspective from Teachers

Abstract

This study explores how Learning by Evaluating (LbE) can be integrated into the 5E instructional model to support Technology and Engineering Education. LbE, influenced by comparative judgment, engages students in analyzing peer work to foster reflection, design reasoning, and iterative thinking. Using qualitative content analysis of teacher interviews, this research investigates how LbE can contribute to each phase of the 5E model: Engage, Explore, Explain, Elaborate, and Evaluate.

Findings suggest that LbE enhances engagement during the Engage phase by leveraging real-world examples and peer comparisons to activate interest and prior knowledge. In the Explore phase, it aids design ideation and constraint recognition, though students often need structure to express their insights. During the Explain phase, LbE supports analytical thinking by helping students distinguish strong and weak designs, yet misconceptions may persist without debriefing. In the Elaborate phase, LbE reinforces the value of feedback and supports refinement of criteria and constraints, serving as a primer for redesign. In the Evaluate phase, it promotes reflection and group communication, though many students struggle to articulate evaluative reasoning without scaffolding.

Overall, LbE offers a flexible and impactful way to deepen learning when intentionally embedded across the 5E framework. However, its success depends on thoughtful implementation and alignment with broader design thinking goals. The study recommends future research to explore how LbE supports long-term learning outcomes and how it may be adapted for diverse classroom settings.

Keywords: Learning by Evaluating (LbE), 5E instructional model, Technology and Engineering Education (TEE), design thinking, comparative assessment, student engagement

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Introduction

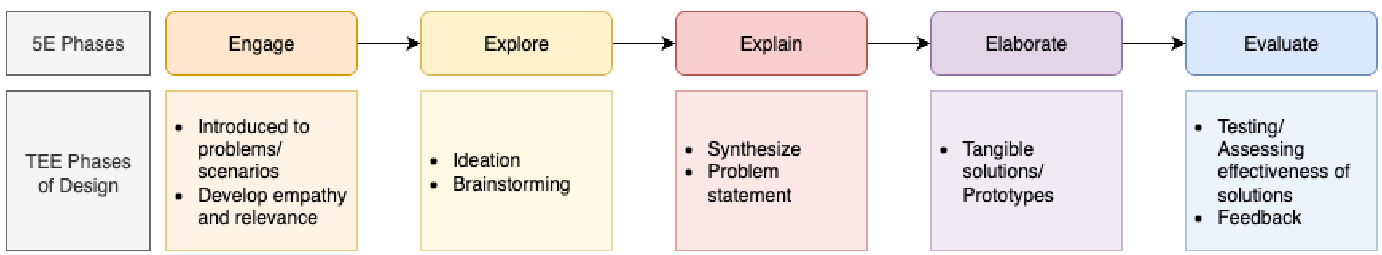
The integration of the 5E Model (Bybee, 2014; Rodriguez et al., 2019) into design thinking education represents a significant advancement in pedagogical strategies (Anggraeni, 2021; Burke, 2014; Elwood et al., 2016; McCurdy et al., 2020). It is also widely used in fields like engineering and technology where problem-solving and innovation are key. This model, with its phases of Engage, Explore, Explain, Elaborate, and Evaluate, provides a structured instructional framework that complements the fluid and dynamic nature of design thinking.

Because the 5E Model constitutes the central framework of this research, it is necessary to provide a more comprehensive account of its origins within the Biological Sciences Curriculum Study (BSCS, n.d.) and its subsequent adaptations (Bybee et al., 1987). Of particular relevance is Burke's 6E Learning byDeSIGN™ Model, which extends the 5E framework by incorporating a sixth phase, **eNGINEER**, to emphasize authentic, design-based engineering practices within Technology and Engineering Education (Burke, 2014). The typographic form of *eNGINEER* (lowercase "e" and uppercase "NGINEER") was deliberately chosen by Burke to align visually with the other five "e" phases while simultaneously highlighting engineering as the distinctive addition to the model. Subsequent research has demonstrated the model's effectiveness in diverse contexts, including supporting student teachers' integration of artificial intelligence applications (Saimon et al., 2024), fostering entrepreneurial skills and STEM career interests among middle school students (Yaşar et al., 2023), enhancing collaboration and reflective learning (Saimon et al., 2024), and improving creativity and motivation when integrated with virtual reality instruction (Lin, 2023). This theoretical progression, from the original BSCS model to its disciplinary adaptation in Technology and Engineering Education (TEE), establishes the foundation underpinning the present study.

The phases of the 5E instructional model align well with the Technology and Engineering Phases of Design (Figure 1).

Figure 1

Alignment of the 5E Instructional Model with the Phases of Technology and Engineering (T/E) Design



The 5E model begin with the ***Engage*** phase, during which students are introduced to real-world problems or user scenarios to foster empathy and contextual relevance. This leads into the ***Explore*** phase, aligned with the ideation component of design thinking, where students generate ideas and investigate possibilities through open-ended inquiry. In the ***Explain*** phase, students analyze and articulate their findings, similar to defining a clear problem statement in design processes. The ***Elaborate*** phase supports the development of prototypes or tangible solutions, reinforcing applied learning and iterative refinement. The cycle concludes with the ***Evaluate*** phase, where students assess the effectiveness of their designs and integrate feedback for improvement.

Like other established instructional design frameworks, such as the ADDIE Model (Analysis, Design, Development, Implementation, and Evaluation) (Branch, 2009) and Gagné's Nine Events of Instruction (Gagné et al., 2005), the 5E model can be applied at multiple levels of instruction, from curriculum design to unit planning to individual lessons (Branch, 2009; Gagné et al., 2005). This scalability is possible because each phase serves as a flexible cognitive and pedagogical guide, rather than a rigid, discipline-specific sequence. As a result, the complete 5E cycle can be meaningfully implemented within a single lesson for any phase of the design process, while maintaining coherence between instructional strategies and learning objectives. In practice, teachers may also adapt the model to accommodate time constraints, curriculum pacing, or assessment requirements, sometimes resulting in a more linear progression. Such adaptations do not diminish the model's inquiry-based nature; rather, they allow educators to emphasize depth within each phase while still fostering opportunities for reflection and refinement (Bybee, 2014; Duran & Duran, 2004).

Yet, the 5E instructional model, developed by Bybee and colleagues, is naturally cyclical, encouraging learners to revisit earlier phases as new insights emerge (Bybee, 2004, 2014; Bybee, Taylor, Gardner, Van Scotter, Powell, et al., 2006). This recursive structure supports continuous refinement of understanding and design solutions, making it particularly well suited to TEE where iteration is a core principle. The 5E model can empower educators to deliver a rich and dynamic learning experience, enhancing students' problem-solving capabilities, creativity, and critical thinking skills (Bybee, 2014). The 5E model aligns naturally with the principles of design thinking, transforming students from passive recipients of knowledge to active contributors in the learning process (McCurdy et al., 2020; Susilowati & Anam, 2017). Through this immersive approach, students develop the ability to navigate and address complex design problems.

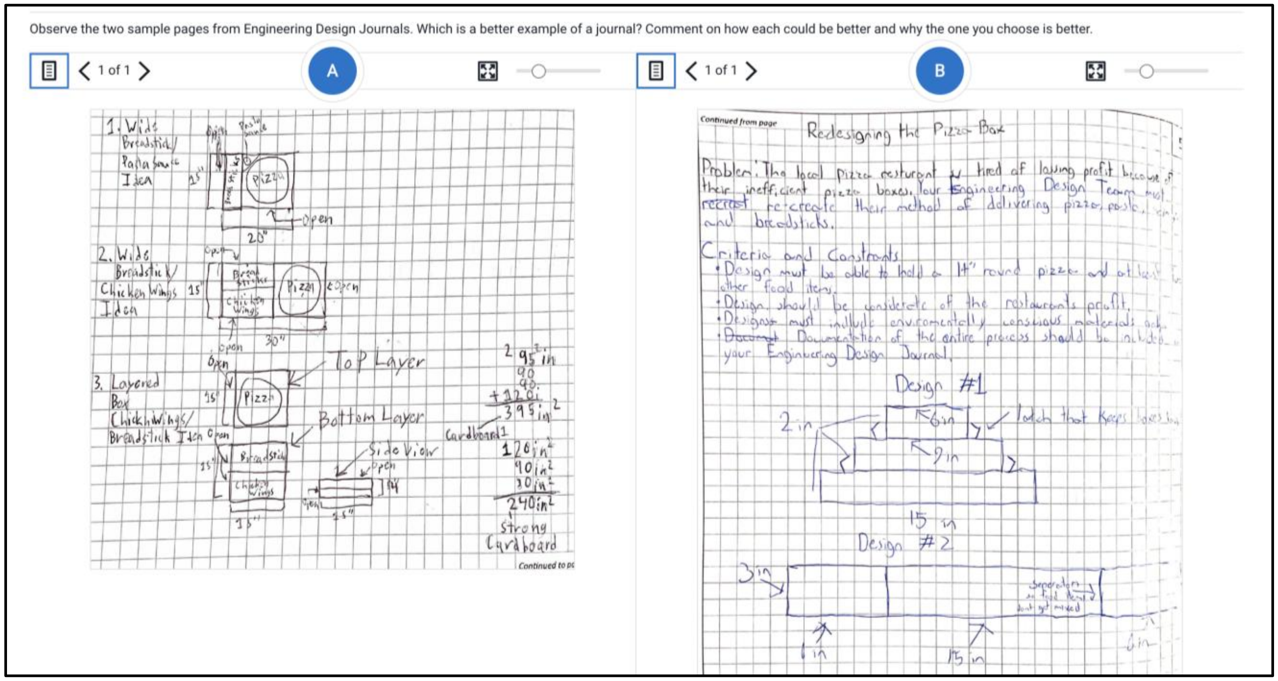
The Engineering by Design (EbD) PreK-12 curriculum, offered by the International Technology and Engineering Educators Association (International Technology and Engineering Educators Association, 2025), commonly leverages the balanced structure and flexibility of the 5E instructional model.

For example, some EbD lessons may complete a full 6E cycle in a single session for a short design challenge (Burke, 2014), while others may extend each phase across several days to support more complex, multi-step projects. EbD's integration of STEM disciplines with English Language Arts and its emphasis on authentic, problem-based learning environments align closely with the 5E model's strengths, particularly its capacity to connect conceptual understanding with applied problem-solving. In the present study, a single cycle of the 5E model was implemented across a curricular unit, with each phase spanning multiple class sessions. This approach provided teachers with the structure needed to meet curriculum pacing and assessment goals while retaining formative feedback, reflective discussions, and opportunities to revisit prior work within and between lessons.

Added to this 5E structure, teachers also incorporated Learning by Evaluating (LbE) (Bartholomew et al., 2020; Jackson et al., 2023; Mentzer et al., 2023, 2024), a pedagogical method derived from adaptive comparative judgment (ACJ). When integrated into the 5E instructional model, LbE may reinforce the model's iterative and inquiry-based learning cycle (Bybee, Taylor, Gardner, Van Scotter, Carlson Powell, et al., 2006; Pollitt, 2012a; Seery et al., 2012), deepening conceptual learning (Flavell, 1979; Veenman et al., 2006) and reflection-oriented design thinking practices (Kolodner et al., 2003; Schön, 1983). ACJ is recognized as a comparative assessment method (Pollitt, 2012b), and has been widely used to appraise the quality of diverse outputs, including student work (Bartholomew et al., 2018; Canty et al., 2017a). It involves a process where individuals compare pairs of items and discern the better according to specified criteria (Figure 2), fostering a deeper understanding and critical evaluation (Bartholomew et al., 2020; Mentzer et al., 2023). Building on this foundation, LbE incorporates a reflective dimension in which students justify their evaluative choices through written commentary and class discussion (Bartholomew et al., 2019b, 2020; Mentzer et al., 2024). This integration of comparative judgment and reasoning has been shown to foster metacognitive awareness by prompting learners to monitor and to strengthen disciplinary understanding (Govaerts et al., 2011; Schön, 1983) and to strengthen disciplinary understanding through repeated engagement with domain-specific criteria and quality exemplars (Bartholomew et al., 2018; Jackson et al., 2023).

Figure 2

Example: Student LbE interface comparing engineering design journals of a pizza box redesign project



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Adaptive Comparative Judgment (ACJ) has been successfully implemented in various educational settings to enhance both student learning and assessment practices. In TEE, ACJ is used to compare student prototypes, where peers evaluate designs based on criteria such as functionality and usability. This process encourages students to critically analyze not only their own work but also that of others, fostering a deeper understanding of design principles (Bartholomew et al., 2019a). Similarly, in writing courses, ACJ has been applied to compare student essays, where students evaluate peer submissions on clarity, argument strength, and structure, which helps improve their own writing and understanding of writing quality (Seery & Canty, 2017). Additionally, in graphic design education, ACJ allows students to compare visual works and assess elements such as aesthetics and clarity of message, enhancing their ability to evaluate design quality (Canty et al., 2017b). These instances demonstrate how ACJ, by facilitating peer comparisons, encourages critical reflection and enhances learning outcomes across different academic areas.

To better understand this synergy, the present study investigated how educators integrate LbE into the 5E instructional framework in the context of introductory TEE courses. Such courses are designed to develop technological literacy, introduce the engineering design process, and cultivate real-world problem-solving skills, and are offered internationally under various titles and curricular frameworks. In the United States, one example is the *Foundations of Technology* (FoT) course, developed by the International Technology and Engineering Educators Association (ITEEA) and implemented in secondary-level programs nationwide. This study focused on FoT to examine how LbE practices align with each phase of the 5E model and how this alignment supports core tenets of design thinking pedagogy.

Table 1 presents a conceptual alignment of the 5E instructional model with LbE, based on prior literature and pedagogical principles rather than empirical findings. Its purpose is to illustrate how LbE can theoretically support and enhance each phase of the 5E model, providing a foundation for the study's analysis.

Table 1

Alignment between the 5E instructional model and LbE

5E Phase	Instructional Focus	LbE Contribution
Engage	Introduce real-world problems and activate prior knowledge	LbE prompts initial critical thinking by presenting past exemplars for analysis, stimulating curiosity and context awareness
Explore	Encourage hands-on ideation and investigation	LbE facilitates peer-to-peer comparison of emerging ideas, guiding students in identifying constraints and possibilities
Explain	Develop conceptual understanding and articulate learning	LbE scaffolds analytical reasoning as students justify their design decisions and identify quality indicators in peer work
Elaborate	Extend learning through application and iteration	LbE supports iterative design improvement through evaluative feedback loops, promoting deeper engagement with content
Evaluate	Reflect on learning and assess outcomes	LbE enables self- and peer-assessment with structured reflection, enhancing students' ability to articulate, critique, and revise their work

Literature Review

Adaptive Comparative Judgment (ACJ)

Adaptive Comparative Judgment (ACJ) is an assessment methodology particularly well-suited for evaluating open-ended tasks in design-centric educational environments. Rooted in Comparative Judgment (CJ) (Thurstone, 1927), ACJ reframes traditional grading by replacing absolute scoring with a series of pairwise comparisons, where judges determine which of two student artifacts demonstrates higher quality. This comparative evaluation process addresses persistent challenges in design education—such as rubric subjectivity and inconsistent criteria interpretation—by enabling more valid and reliable judgments of student work through iterative pairwise comparisons (Pollitt, 2012a; Seery et al., 2012).

What differentiates ACJ from earlier comparative approaches is its adaptive algorithm, which dynamically refines the pool of comparisons. Early rounds involve randomly selected pairs, but as judgments accumulate, the system begins presenting items of similar rank. This adaptivity increases efficiency and precision, allowing for fine-grained distinctions between designs that are close in quality (Bramley & Vitello, 2019). Such capability is particularly advantageous in TEE, where students' prototypes, sketches, or reflective journals often vary along multiple dimensions—functionality, creativity, usability, and technical accuracy—and resist reliable quantification (Bartholomew et al., 2019b; Kimbell, 2022; Seery et al., 2012).

Adaptive Comparative Judgment (ACJ) has been successfully implemented in various educational settings to enhance both student learning and assessment practices. Pollitt's (2012b) seminal application of ACJ in a large-scale writing assessment demonstrated its practical value and user acceptance, as trained educators found the pairwise judgment process more transparent and meaningful than traditional marking. In the context of TEE, similar implementations have yielded promising outcomes (Bartholomew et al., 2019a). For example, Seery et al. (2012) employed ACJ to evaluate students' design projects, highlighting how the method not only improved assessment reliability but also supported deeper pedagogical engagement. Judges, often teachers or subject experts, reported that evaluating side-by-side work prompted more reflective and discipline-specific conversations around quality.

Furthermore, research has shown that ACJ is not limited to summative evaluation but can function as a pedagogical strategy for formative learning. Bartholomew et al. (2019) and Potter et al., (2017) illustrated how ACJ encourages students to analyze exemplar work, identify key quality features, and internalize criteria for success. Additionally, in graphic design education, ACJ allowed students to compare visual works and assess elements such as aesthetics and clarity of message, enhancing their ability to evaluate design quality (Canty et al., 2017b). These instances demonstrate how ACJ, by facilitating peer comparisons, encourages critical reflection and enhances learning outcomes across different academic areas. This makes ACJ particularly compatible with instructional models such as the 5E framework, where iterative exploration and reflection are central. In design-oriented classrooms, ACJ fosters critical thinking by placing students in the role of evaluators, thus reinforcing their disciplinary identity and metacognitive growth.

Recent studies in design and technology education have also integrated ACJ with ipsative assessment approaches, which emphasize student progress by comparing current performance to their own prior work rather than to external benchmarks or standardized criteria (Seery et al., 2019). This positions ACJ as not just a grading tool, but as a learning mechanism aligned with inquiry-driven and student-centered pedagogies commonly used in STEM and engineering education.

To summarize, ACJ provides a powerful alternative to traditional assessment in TEE classrooms. Its focus on holistic judgment, combined with adaptive refinement, supports both instructional fidelity and student learning. When integrated intentionally into classroom practice, ACJ aligns well with the pedagogical goals of design thinking and offers a strong foundation for the LbE model.

Learning by Evaluating (LbE)

Learning by Evaluating (LbE) is an emerging pedagogical strategy that leverages the cognitive and reflective processes embedded in ACJ to prime and support student learning in design-based contexts. While ACJ traditionally involves expert judges comparing student work through a sequence of pairwise evaluations to establish a reliable rank order (Pollitt, 2012b), LbE adapts this process by engaging students as evaluators and transforming assessment into a priming, learning activity rather than an outcome (Bartholomew & Jones, 2022; Mentzer et al., 2023).

In TEE settings, student artifacts are inherently multidimensional, reflecting aspects such as creativity, functionality, and usability. Traditional rubric-based assessments frequently fail to capture the full complexity of these elements, limiting their effectiveness when guiding student work or later, evaluating student learning and design quality (Bartholomew et al., 2018; Crismond & Adams, 2012; Kimbell & Stables, 2007). LbE addresses this challenge by first, facilitating side-by-side comparisons guided by an adaptive algorithm, allowing students to make holistic judgments while reflecting on the criteria that define effective work (Thorne et al., 2024). Then, through structured commentary, students are encouraged to justify their decisions, thereby deepening metacognitive engagement and supporting the development of transferable evaluative skills (Bartholomew et al., 2020; Seery et al., 2012).

Recent research has demonstrated that LbE fosters meaningful reasoning, conceptual understanding, and improved design quality, particularly when implemented early in the design process. Rather than passively observing exemplars or receiving feedback retrospectively, students actively participate in evaluating authentic artifacts such as Point of View (POV) statements, sketches, or design journals created by peers or previous cohorts (Mentzer et al., 2024). This evaluative engagement serves as a priming mechanism, encouraging students to recognize disciplinary norms and quality indicators before initiating their own design tasks (Jackson et al., 2023; Thorne et al., 2024).

By integrating LbE into the 5E instructional framework, educators can align this pedagogical practice with key phases of the model, particularly Engage, Explain, Elaborate, and Evaluate. During the Engage phase, LbE activates prior knowledge and highlights real-world relevance through exposure to peer work. In the Explain and Elaborate phases, students construct and revise their own designs with reference to evaluative feedback and peer comparisons. Finally, in the Evaluate phase, LbE fosters structured reflection and justification of learning, reinforcing the iterative nature of both design thinking and inquiry-based learning.

In sum, LbE represents a potentially powerful facilitator of formative assessment, critical reflection, and disciplinary thinking. When applied within structured instructional models like the 5E framework, it not only enhances learning outcomes in TEE but also cultivates students' capacity for thoughtful evaluation, design iteration, and lifelong learning.

5E Instructional Model

The 5E Instructional Model was first conceptualized during a BSCS curriculum initiative in the mid-1980s, with early descriptions and rationale articulated by Bybee (2004) and its seminal framework and supporting research formally published by Bybee et al. (2006). Initially developed to strengthen biological science education, the model organizes learning into five iterative phases: Engage, Explore, Explain, Elaborate, and Evaluate. Each phase fulfills a distinct cognitive and pedagogical role, guiding students from eliciting and connecting prior knowledge to applying new ideas and assessing understanding. The 2006 BSCS report details the model's theoretical grounding in constructivist and inquiry-based learning, as well as empirical evidence of its effectiveness in promoting deep conceptual understanding, knowledge retention, and transferable problem-solving abilities. Although originally intended for science curricula, the 5E structure has demonstrated adaptability to a wide range of disciplines, including TEE (Burke, 2014), where its emphasis on iterative learning and active engagement aligns with the goals of design-based instructional practices.

The 5E Model in teaching and learning is an instructional approach that fosters an engaging, student-centered classroom environment (Bybee, 2009, 2014; Joswick & Hulings, 2024; Susilowati & Anam, 2017). The 5E Instructional Model, renowned for fostering student-centered learning environments, has gained substantial traction within TEE realms (Bybee, 2019; Chayati et al., 2020). This model, underpinned by constructivist learning theories, is tailored to meet the unique pedagogical requirements of these disciplines, as evidenced by its extensive coverage in contemporary academic literature (Bybee, 2009, 2019). Table 2 outlines the application of the 5E Model in a technology/engineering design thinking context.

Table 2

5E Model in the design thinking context

Phase	Details
Engage	This initial phase is pivotal for integrating real-world engineering challenges into the learning framework. It leverages industry-relevant scenarios to pique students' interest, thereby establishing a direct connection between academic concepts and their practical applications.
Explore	During this stage, students engage in collaborative problem-solving and hands-on experimentation. Activities such as prototyping, coding, and model-building are central, facilitating the application of theoretical knowledge to practical tasks.

Explain	This phase involves a collaborative dialogue between students and educators, focusing on the analysis and discussion of the exploration outcomes. It serves as a conduit for introducing and assimilating technical terminology and formal concepts within the context of their empirical experiences.
Elaborate	Tailored to extend learning, this phase involves more intricate or extensive project work. Students are encouraged to refine their solutions, incorporate advanced technologies, and consider the broader societal and environmental implications of their work.
Evaluate	The evaluation phase transcends traditional assessment methods by incorporating peer reviews and reflective practices on the design process and final outcomes. This comprehensive assessment strategy focuses on both technical skills and the overall problem-solving methodology, highlighting the importance of continuous improvement and practical relevance.

The integration of the 5E Model in TEE cultivates a dynamic learning environment where students actively engage in experiential learning, collaborative problem-solving, and the application of classroom concepts to real-world challenges (Chayati et al., 2020; Susilowati & Anam, 2017).

In 2010, the International Technology and Engineering Educators Association (ITEA/ITEEA), through its Engineering byDesign™ (EbD™) curriculum (https://www.iteea.org/6e-learning-bydesign), introduced the 6E Learning byDeSIGN™ Model, which comprises Engage, Explore, Explain, eNGINEER, Enrich, and Evaluate, as an instructional framework tailored specifically for Technology and Engineering Education (Burke, 2014). Developed independently within EbD, the 6E framework was designed to address the distinctive goals of TEE by positioning engineering design as the central means for students to apply concepts, practices, and attitudes (Burke, 2014). In doing so, the model integrates design-based problem solving with inquiry-oriented learning and underscores technological literacy as a core outcome, thereby strengthening the instructional foundation for TEE.

Method

This study examined how teachers integrated LbE within the ITEEA EbD Foundations of Technology (FoT) course to enhance engineering design experiences. Participating teachers had previously engaged in professional development on ACJ and LbE through an ongoing district–university collaboration that began in 2022. They attended at least two PD sessions each academic year, where they were trained on using ACJ software and designing lessons that embed LbE into FoT instruction. Teachers adopted these strategies to help students evaluate the quality of peer design artifacts, articulate reasoning behind evaluative choices, and refine their own design thinking before starting projects.

High school teachers from a culturally and linguistically diverse district (DeKalb County School District, 2021) voluntarily participated in semi-structured interviews conducted both virtually and in person. Interviews explored their experiences and perspectives on integrating LbE in FoT, including specific classroom practices and perceived impacts on student learning. Data were analyzed using Qualitative Content Analysis (QCA) to identify patterns and themes. Two researchers coded independently, resolving discrepancies through discussion, and investigator triangulation was used to support reliability.

Research Context

This research was conducted in collaboration with DeKalb County Public Schools in Atlanta, Georgia, characterized by its extensive cultural and linguistic diversity. According to district reports (DeKalb County School District, 2021), the student body represents over 155 nationalities and speaks more than 185 languages. The district's TEE program includes the FoT (International Technology and Engineering Educators Association [ITEEA], 2025) as the introductory course in the high school pathway. The course centers on technological literacy, engineering design, and real-world problem-solving, with the engineering design process reinforced through multiple authentic, design-based learning experiences. Lessons in the course are structured with the 6E instructional model.

Since 2022, the district has partnered with our research team to embed LbE into FoT instruction. Initially piloted with a small group of teachers, this collaboration expanded in subsequent years to include broader participation and iterative refinement of LbE strategies. By the time of this study, participating teachers had multiple years of experience integrating LbE and were using it both at the onset of major design projects and throughout the design cycle. Students engaged by comparing designs from prior cohorts through ACJ-based LbE activities, enabling them to practice evaluative judgment, discuss quality criteria, and apply insights to their own projects.

In participating FoT classrooms, LbE was implemented using ACJ to compare anonymized student design artifacts from previous cohorts before students began their own projects. Teachers selected a set of artifacts that represented a range of quality and approaches related to the current design challenge. During the pre-project phase, students engaged in multiple comparisons, each time choosing the stronger of two artifacts based on a comparison prompt from the teacher (e.g., Which shows better structural integrity?, functionality?, aesthetics?) and recording short justifications for their choices. The insights from these comparisons informed students' design planning, with teachers facilitating discussions that connected observed strengths and weaknesses to the design criteria. In some cases, teachers also incorporated a mid-project implementation of LbE to allow formative peer evaluation of in-progress prototypes, further reinforcing iterative improvement. Following project completion, students participated in a final ACJ round to evaluate current class artifacts, with justifications again collected for analysis.

Participants

In Spring 2023, participants included FoT teachers from five high schools within the district. The FoT course was selected as the focus because it is a foundational component of the district's TEE curriculum and offers rich opportunities to examine design thinking across diverse student populations. These teachers had varying years of teaching experience but shared a common background of LbE PD participation since at least 2022.

Data Collection

In this study, data were collected using the semi-structured interview technique, a method extensively acknowledged as the principal data collection tool in phenomenological research. This method is particularly advantageous for exploring complex and nuanced subjects, as it allows for both guided and open-ended questioning. The semi-structured interview format facilitated a comprehensive exploration of the teachers' experiences and perceptions while providing the flexibility to uncover new insights, as outlined in relevant research methodology literature (Adams, 2015; Harrell & Bradley, 2009). This technique is particularly suited to our study's objective of understanding the nuances of technology education in diverse classroom settings.

The interviews were administered by two members of the research team, The duration of the interviews varied, with a minimum length of 45 minutes and maximum of an hour and a half. This range ensured a sufficient depth of conversation to explore the research questions comprehensively.

Data Analysis

Transcriptions of interviews were conducted electronically utilizing web-based transcription software to facilitate a prompt and efficient preliminary text. Firstly, in adherence to ethical research practices and to maintain confidentiality, all identifiable information, such as the names of the participating teachers, was redacted from the interview transcripts. Subsequently, each teacher was assigned an alias, ranging from Teacher A to Teacher E, to facilitate anonymous yet distinct referencing throughout the analysis and discussion phases of the study. Finally, to ensure accuracy and fidelity to the original audio, two researchers reviewed the automated transcriptions by listening to the recordings and making necessary corrections. This secondary review process was essential for validating the transcriptions, adjusting any discrepancies, and refining the text to accurately reflect the content of the interviews.

In the transcription of the interviews, verbatim accuracy was prioritized to preserve the authenticity of the participants' responses. Grammatical inconsistencies inherent in spoken language were retained, except in instances where such irregularities impeded the clarity and context necessary for interpreting the teachers' answers. This approach ensured that the data analysis was grounded in the actual language used by the participants, reflecting a true account of their expressed views and experiences.

Subsequent to the anonymization of the interview transcripts, the research team undertook a thorough and iterative review of the interviews. This involved multiple readings of the interview content to gain a comprehensive understanding of the data. This process of immersion is a critical step in qualitative analysis, as it enables researchers to familiarize themselves deeply with the nuances and intricacies of the responses, thereby laying a solid foundation for the subsequent coding and analysis phases.

In the analysis of the data accrued from this study, we employed a deductive analysis approach, as delineated in the previous literature (Elo & Kyngäs, 2008; Polit & Beck, 2004). Our analysis was guided by a flexible coding framework (Table 3) informed by phases of the 5E instructional model.

Table 3

Example coding prompt: "How does LbE affect your use of design thinking in teaching?"

Engage	**Contribution**: Engages students by providing real-world contexts that pique their interest in design thinking, fostering curiosity. **Hindrance**: If not carefully framed, LbE can overwhelm students with complexity before they grasp the fundamentals of design thinking.
Explore	**Contribution**: Allows students to actively engage in problem-solving, promoting hands-on exploration of design concepts. **Hindrance**: Without structured guidance, students may focus on the experience rather than the exploration of design principles.
Explain	**Contribution**: Encourages students to reflect and articulate their design thinking processes, enhancing their understanding. **Hindrance**: Students may struggle to verbalize their thought process without a clear framework linking the experience to design thinking.
Elaborate	**Contribution**: Requires students to apply design concepts in new, complex situations, which deepens their design thinking skills. **Hindrance**: Students might face difficulty in abstracting and applying learned design thinking concepts to different contexts without explicit connections.
Evaluate	**Contribution**: Facilitates the evaluation of students' understanding and application of design thinking through both process and product assessment. **Hindrance**: Measuring the impact of LbE on students' design thinking can be challenging without clear evaluative criteria linked to design thinking objectives.

This framework allowed for structured yet adaptable categorization of data aligned with each phase of the model. Within this framework, we developed predefined categories aligned with the core phases of the 5E Model. This methodological choice was particularly apt, given that deductive content analysis is appropriate for examining the applicability of existing theories or models within new contexts (Marshall & Rossman, 2014). This structured approach facilitated a focused examination of the data, enabling us to assess the integration and pedagogical contribution of LbE within 5E Model-driven instruction, particularly in the context of design thinking.

Findings

Engage Phase: Stimulating Interest and Activating Prior Knowledge

The Engage phase serves as the launch point for student learning, where curiosity is sparked and prior knowledge is surfaced. In the context of this study, LbE was implemented in the Foundations of Technology (FoT) course as a strategy to deepen engagement during this early stage. Teachers reported that comparative analysis of past student work, supported by guided prompts, warm-up questions, and real-world scenarios, helped students enter the design process with greater enthusiasm and a clearer understanding of expectations. The benefits of LbE in this phase included heightened classroom engagement, early activation of sketching and brainstorming, and the formation of conceptual bridges to upcoming content. However, several instructional limitations emerged, including the risk of overshadowing content, engagement fatigue, and the need for more intentional integration with the broader design thinking framework.

Benefit 1: Boosts Engagement in Class

Teachers consistently reported that LbE increased student motivation and attention at the start of a unit. By exposing students to tangible examples of peer-designed artifacts, ranging from packaging prototypes to furniture concepts, students could visualize success criteria in accessible ways. Teacher A described the value of LbE in reaching diverse learners:

> "Um, I like the different way of approaching the lessons, and I think it just gives me a better way of reaching the students. So I think it's beneficial not only with this group, but also with some of my other classes."

For example, in a unit on ergonomic desk design, students were shown contrasting examples from previous years: one a cluttered, unstable build, and the other a minimalist, functional prototype featuring user-centered elements like adjustable height and cable management. As students debated which design better addressed user needs and why, they began to internalize key design principles such as stability, aesthetics, and functionality. In another class focused on wearable tech, students compared a well-fitted fitness tracker mock-up with a bulky, impractical version that lacked user input. Teachers noted that these side-by-side comparisons quickly generated excitement and meaningful discussion about real-world use, anchoring the abstract design goals in tangible, student-produced outcomes.

Benefit 2: Initiates Sketching and Brainstorming

LbE also served as a scaffold for launching student ideation and sketching. Rather than starting with a blank page, students entered brainstorming sessions equipped with evaluative language and visual anchors drawn from peer exemplars. Teacher D explained:

> "It gets them prepared to do a better job with the lesson or whatever I'm putting out."

In a bridge design lesson focused on truss systems, students reviewed digital portfolios from past cohorts. One featured carefully annotated sketches and a clear explanation of load distribution; the other lacked structure and coherence. Students reflected on how detailed planning shaped structural integrity, and they approached their own sketches with greater intention and organization. In another case, during an assistive device challenge, students examined wheelchair attachment prototypes. Seeing how earlier teams diagrammed user scenarios and failure points helped current students expand their brainstorming beyond aesthetics and toward user-centered function and empathy.

Benefit 3: Creates Connection to Concepts

Beyond engagement and preparation, teachers highlighted LbE's ability to activate prior knowledge and connect it to new design content. Teacher C observed:

> "… that really kind of gives them a starting point you know we talk about the kids having like prior knowledge that kind of pulls out their prior knowledge before we even start the concept."

Before a unit on renewable energy, for instance, students compared solar-powered phone charger prototypes—one compact and efficient, the other bulky and impractical. The contrast led to class discussions on portability, solar panel angle, and real-world application. In another example, a robotics unit began with students evaluating simple autonomous vehicle models. They noticed how different wheel configurations, sensor placements, and code structures impacted function. These early observations helped frame their thinking before diving into technical lessons.

Challenge 1: Risks of Overshadowing Content

Despite these instructional benefits, teachers warned that LbE could unintentionally steer students toward surface-level engagement if not explicitly connected to deeper learning goals. Teacher A recalled:

> "But it was horrible because I was really trying to get them to understand the different ways we can approach the engineering design project ... like brainstorming multiple solutions, sketching initial concepts, or revising based on feedback ... but they were stuck on thinking there was only one right answer. It was frustrating because I wanted them to see that design is about iteration and exploration, not just following steps."

In one lesson on materials and structure, students became overly focused on the sleek aesthetics of a previous year's prototype. As a result, they neglected the day's instructional goal of exploring tensile strength and material properties. In another example, students fixated on decorative features in a chair redesign task (such as paint color and logos) without considering load-bearing calculations. These moments highlighted the need to foreground technical reasoning during LbE discussions.

Challenge 2: Engagement Fatigue

Another challenge arose when LbE was used too frequently or in a repetitive format. While students initially engaged with the activity, repeated exposure to numerous comparison pairs, even when the artifacts were visually different (such as multiple sets of brainstorming sketches), diminished its instructional impact. This suggests that the effectiveness of LbE may rely less on its novelty and more on the quality of critical thinking it demands. However, because sustained critical analysis can be cognitively taxing, overuse without variation may reduce students' motivation and enjoyment. Teacher B shared:

> "They got bored sometimes, really. At first, they were into it—comparing other students' work and figuring out what made one better than the other. But when we kept doing the same kind of comparison activity, like with similar worksheets or formats, it started to feel repetitive. I think they needed more variety or a clearer purpose each time, otherwise it just became another task to get through."

In one semester, students engaged with LbE for units on packaging, assistive devices, and architectural modeling, all using static worksheets and written prompts. Teachers noted that while early activities sparked rich dialogue, later ones were met with minimal reflection. Several suggested incorporating rotating strategies, such as gallery walks, digital peer voting tools, or collaborative rubrics that evolve with each unit, to reinvigorate participation.

Challenge 3: Difficulty Linking to Design Thinking

Finally, some teachers identified a disconnect between LbE activities and the broader design thinking process. Without explicit scaffolding, students occasionally viewed LbE as a stand-alone task rather than a component of iterative problem-solving. Teacher E highlighted:

> "I think the issue with doing more is really being intentional… having the time to be intentional."

In one unit on wearable health tech, for example, students successfully evaluated sample projects but then failed to apply those insights to their own planning. Without being prompted to carry forward specific features—like data visualization or user testing procedures—they defaulted to generic solutions. Teachers emphasized the need for reflection prompts, linking questions, or direct modeling to bridge the gap between evaluation and action.

Explore Phase: Encouraging Inquiry and Design Possibilities

The Explore phase invites students to investigate design problems, interact with materials or ideas, and begin developing preliminary solutions. In the 5E instructional model, this phase emphasizes inquiry-based learning – where students make observations, gather data, and test assumptions without immediate teacher-led explanation. Within the design thinking framework, this aligns closely with the ideation stage, where learners brainstorm possibilities after empathizing with user needs. The integration of LbE during this phase allowed students to explore existing solutions, compare multiple approaches, and begin envisioning innovations of their own. Two key instructional benefits emerged: students became more confident and creative in their ideation, and they engaged more actively in exploring design constraints and opportunities. However, a notable challenge was students' difficulty in articulating learning outcomes from LbE activities, especially when reflection was not structured.

Benefit 1: Aids Design Ideation

Teachers found that comparative analysis during this phase stimulated original thinking and discouraged rote replication. By reviewing diverse examples of peer work, students developed a better sense of what had already been done—and where there was room for novelty. Teacher D described this in the context of a challenge requiring students to invent a unique backpack:

> "And so I would give them all of those different examples and see if they could use them to come up with a unique idea, because my challenge was for them to create a backpack that didn't already exist. I get more excited when they think creatively and come up with something totally different."

This activity highlights the essential role of LbE in the ideation process. Students engaged in early comparative thinking to extract common design patterns, then diverged by identifying unmet needs and overlooked features. The practice mirrors the divergent thinking encouraged in design thinking, where multiple ideas are generated after users and constraints are studied. LbE, when used in this way, helps students avoid surface-level solutions and push toward more innovative and empathetic designs.

Benefit 2: Promotes Active Exploration

LbE also served as a launchpad for hands-on sketching and experimentation. Teachers used LbE to transition students from passive observation to active creation—an essential part of both the 5E model's Explore phase and design thinking's rapid prototyping mindset. The comparative nature of LbE supported students in understanding criteria such as usability, feasibility, and function, which then guided their own exploratory efforts. Teacher B illustrated this use:

> "Um, I used it as a primer for sketching. We had talked about sketching um earlier but I knew we were getting ready to get into technical sketching. So I, I wanted some of those um concepts were overlap and so we did it, so I definitely think it was a primer."

Here, the use of LbE functioned as a cognitive bridge. Students who had previously been introduced to basic sketching returned to the practice with deeper purpose, as they now had visual models and evaluative language to support their decisions. This mirrors the transition from ideation to prototyping in design thinking, and the hands-on inquiry expected in the 5E model's Explore phase. Rather than diving blindly into design, students were actively experimenting with structure and representation using comparative reasoning.

Challenge: Difficulty Articulating Learning

Despite these clear benefits, teachers noted that some students struggled to articulate what they had learned from LbE tasks. This challenge appeared when the comparison activities were not accompanied by structured reflection prompts or facilitated discussions. In the 5E model, the transition from Explore to Explain is critical—moving students from experience to conceptual understanding. Without scaffolding, however, students often remained in an experiential space without deeper synthesis. Teacher E shared this concern:

> "Um, well, the biggest is [providing] them not confusing criteria because that's right after the lesson, you know…"

Similarly, Teacher A highlighted a more conceptual version of this problem:

> "The challenge lies in the transition from hands-on experiences to conceptual understanding. If the structure is lacking, students are left with experiences they enjoy but cannot describe or learn from in a meaningful or transferable way."

These observations reveal a common pedagogical gap: while LbE activities offered rich visual and cognitive input, students needed more support to make their learning explicit—a key demand in both the Explain phase and the reflection component of design thinking. Without this step, students might produce more thoughtful sketches or engage more eagerly in exploration, but they lacked the metacognitive tools to explain why they made particular design decisions or what principles guided their choices.

When applied during the Explore phase, LbE enabled students to generate original ideas, engage in productive exploration, and interact with design criteria through meaningful comparison. These actions align closely with the goals of both the 5E instructional model and design thinking pedagogy: fostering inquiry, encouraging experimentation, and beginning to construct informed hypotheses. However, the full benefits of LbE during exploration depend on what happens next. Without guided transitions into reflection, discussion, or conceptual framing, students may experience the phase as disjointed or incomplete. Therefore, the thoughtful design of post-LbE prompts, group debriefs, or sketch annotations is essential for turning rich experiences into transferable learning – laying the groundwork for the next phase of instruction.

Explain Phase: Clarifying Understanding and Deepening Reasoning

In the 5E instructional model, the Explain phase serves as the critical moment when students transition from inquiry-based exploration to formalizing their understanding. This is the point where teachers introduce terminology, guide students to articulate conceptual insights, and begin to clarify previously observed phenomena. In the context of design thinking, this phase parallels the synthesis and framing stage—where students not only iterate on ideas but also learn to express the reasoning behind their design choices. LbE contributed meaningfully to this phase by supporting concept consolidation, offering strong and weak design exemplars, and correcting misconceptions that arose during exploration. However, teachers also noted that if LbE was not followed by intentional debriefing, it risked reinforcing errors rather than correcting them.

Benefit 1: Smoothens Conceptual Transition

Teachers found that LbE helped bridge students' initial exploration with abstract conceptual framing. By allowing students to observe and evaluate peer work just before formal instruction or direct teaching, teachers were able to reference student-generated insights and language, making new concepts feel grounded in familiar experiences. Teacher A illustrated this benefit when discussing how a student connected aesthetics and accessibility to universal design:

> "Well, I came across one student response during our first-period class that really stood out—it was a great example because the student actually talked about the aesthetics of their design. We had been discussing universal design in class, focusing on how products should be easy for everyone to use, no matter their age or ability. This student wrote about how their backpack could be grabbed easily, how the straps were adjustable for different body sizes, and how the color choice made it easier to find in low light. I was like, 'Yes, this is what you need to be thinking about.' It showed that they were really connecting what we had talked about—why we design,

> how we design, and the importance of making things accessible for everyone."

In this example, the teacher was able to reinforce inclusive design principles by anchoring them to a student's evaluation in the LbE session. Rather than teaching abstract concepts from scratch, the teacher used the student's commentary as a springboard to introduce universal design, connecting aesthetics with user functionality – one of the central goals in both human-centered design and iterative engineering.

Benefit 2: Provides Quality Examples

Another strength of LbE in this phase was its ability to provide students with both positive and negative examples of design work. These comparative samples supported clearer understanding of quality benchmarks and common pitfalls. In design thinking, showing examples of *"what works"* and *"what doesn't"* allows students to learn through others' iteration cycles—essentially accelerating their own development. Teacher D highlighted this approach:

> "Well. I want to pull my students' work the ones that I feel like are stellar and take pictures of goals. Also want to put some stuff that's not so good, you know in there and have them to see why um those are gonna be the most beneficial because I look at that, that VEX Robotics, they have a sample workbook, design workbook and I think it's very a good example for students to use…"

By integrating exemplary and flawed work into the Explain phase, students were able to analyze designs based on real peer-created content rather than hypothetical models. This practice also reflects what the 5E model aims to accomplish in Explain: allow students to take ownership of ideas by referencing prior evidence and experiences, while simultaneously giving teachers opportunities to formally name and reinforce design vocabulary.

Benefit 3: Corrects Misconceptions Through Clarified Reasoning

In addition to helping students recognize quality work, LbE was noted as a tool to preemptively address common design misconceptions. Through comparing work samples and reflecting on design choices, students became more aware of the purpose behind design protocols and engineering practices. This aligns with design thinking's emphasis on intentionality – not just creating a product, but understanding why certain choices lead to better outcomes. Teacher C commented on this:

> "…should not make students make the mistakes that I've seen in the past to make sure that they're conscious of why they have to do it a certain way…"

By surfacing these errors before students began prototyping or testing, LbE helped clarify reasoning and reduce the likelihood of repeating basic design flaws. It also laid the groundwork for more confident decision-making in later phases, such as elaboration and evaluation.

Challenge: Risks of Perpetuating Misconceptions

However, the effectiveness of LbE in the Explain phase depended heavily on the accuracy and intentionality of instructional follow-up. Several teachers noted that if students evaluated peer work without proper facilitation, or if flawed examples were not clearly contextualized, there was a risk that misconceptions could be internalized rather than corrected.

While no specific quote directly captured this concern in one statement, it emerged across teacher interviews as a cautionary note: without structured debriefing, students might confuse critique with correctness. For example, if a poorly annotated sketch was not explicitly discussed as an example of what not to do, students might infer that this level of detail was acceptable. Similarly, if peers misused design terms during their LbE commentary, those misunderstandings could spread without correction. These scenarios highlight a broader issue: although students were asked to make holistic quality judgments, design artifacts often contain multiple dimensions such as functionality, aesthetics, and clarity of communication. Without guidance to understand trade-offs or the relative weight of these dimensions, students may carry forward misconceptions about what is valued, potentially reinforcing superficial or incorrect interpretations of quality.

This challenge underscores a core tenet of both the 5E model and design thinking: reflection and explanation must be directed. The Explain phase is not just about allowing students to talk – it's about helping them refine their understanding with accuracy and purpose.

In conclusion, LbE served as a powerful tool for deepening conceptual clarity and refining evaluative judgment during the Explain phase. It enabled teachers to use student-driven observations to introduce key design concepts, supported visual learning through real examples, and surfaced common errors for class-wide correction. These practices are well-aligned with both the 5E model's emphasis on evidence-based conceptual development and design thinking's iterative learning processes. However, the potential for misunderstanding remains if educators do not actively mediate the reflection process. When supported with thoughtful prompts and strategic facilitation, LbE becomes not just a way to explain, but a way to clarify, challenge, and co-construct meaningful design learning.

Elaborate Phase: Deepening Design Thinking through Feedback, Criteria, and Redesign Readiness

In the 5E instructional model, the Elaborate phase is where students extend their understanding by applying core concepts in new contexts. In design thinking, this is analogous to the iteration stage, where designers revisit and refine their work based on evolving criteria, user feedback, and emerging insights. Within the observed classrooms, LbE played a transformative role in this phase, not just as a retrospective activity, but as an instructional lever to support forward-facing reflection, targeted revisions, and a more critical orientation to design development. Teachers noted that LbE helped students internalize the value of feedback, sharpen their design criteria, and prime them for new challenges, making it a uniquely effective tool for fostering iterative thinking and future-oriented creativity.

Benefit 1: Emphasizing the Importance of Feedback in Iteration

In traditional school settings, feedback often appears as teacher comments at the end of an assignment – too late to be acted upon. In contrast, LbE positioned feedback as a central, dynamic part of the learning process, aligning with design thinking's ethos that meaningful design is achieved through cycles of reflection and response. Teachers used LbE to explicitly teach students how to seek, value, and incorporate feedback into their design processes not as correction, but as collaboration. Teacher B captured this shift in mindset:

> "… For me, I want to hit home, you gotta design and feedback is important. How are you gonna know how to make it better? And sometimes somebody has made it better and they can tell you what you can do and you need them to tell, right? So for me that's what I wanted them to carry away. Like the importance of wanting that feedback to make your products better. And so we'll see…"

This commentary reflects a core tenet of both the Elaborate phase and design thinking pedagogy: that feedback is not an interruption to learning, but an accelerator of insight. By using peer comparison and reflective prompts, LbE transformed feedback from something students received passively into something they actively pursued and applied.

Benefit 2: Refining Design Criteria and Constraints through Reflective Evaluation

Beyond emphasizing feedback, LbE also gave students structured opportunities to re-examine the criteria and constraints that guided their work. Teachers leveraged these comparisons to challenge students' assumptions about what mattered most in their designs – whether it be functionality, user-centeredness, feasibility, or aesthetic quality. This practice aligns with the Elaborate phase's emphasis on applying new knowledge and supports design thinking's iterative nature, where the problem definition evolves as insights accumulate. Teacher A explained this pedagogical focus:

> "And what, like, so they go through all the steps in the design cycle each time, but when I get to a new step, it's really focused on that, like the last one, although they did the whole process, my real focus was on them coming up with good criteria and constraints."

Here, LbE allowed students to zoom in on specific stages of the design cycle, particularly the formulation of design goals and limitations. By comparing past projects that succeeded or failed to meet intended constraints, students developed a more nuanced sense of what makes criteria meaningful, specific, and usable. They began asking deeper questions like: Is this constraint measurable? Does this criterion align with the user's need? This step worked as a clear indicator of maturing design thinking.

Benefit 3: Serving as a Primer for Redesign and Application

Teachers also described LbE as a conceptual on-ramp to future learning tasks. Rather than launching straight into new content or requiring full redesigns from scratch, they used LbE to activate prior knowledge, draw attention to learning gaps, and prime students to think more critically in their next iteration. In this way, LbE served as an efficient and cognitively rich substitute for traditional do-over assignments.

This use of LbE reflects the forward momentum of the Elaborate phase: students were not merely revisiting their work, but preparing to level up. By reflecting on what they and others had done, students became more aware of design trade-offs, more articulate in justifying their choices, and more strategic in planning what to do differently next time. In short, LbE made their design learning recursive and intentional, rather than linear and task-bound.

In the Elaborate phase, LbE emerged as a pedagogically rich strategy that pushed students to internalize feedback, revise their design logic, and ready themselves for future innovation. It shifted students' orientation from merely completing tasks to learning through evaluation, which is a hallmark of both high-quality STEM education and authentic design practice. By integrating LbE into this stage, teachers helped students realize that effective design is not just about what you create, but how thoughtfully you can improve it. This marks a critical shift from being a builder to becoming a reflective designer, a shift that lies at the heart of both the 5E model and design thinking frameworks.

Evaluate Phase: Synthesizing Learning and Articulating Design Reasoning

Benefit 1: Enhances Collaborative Evaluation and Communication

In the Evaluate phase of the 5E instructional model, students are expected to reflect on what they've learned, demonstrate mastery, and communicate their understanding. Similarly, in design thinking, this phase corresponds to the stage of testing, reflection, and communicating the value of design choices. In the observed classrooms, LbE helped reinforce the habits of reasoning and reflection necessary for this phase, particularly in collaborative settings. However, while students showed growth in group communication and project synthesis, teachers noted persistent challenges in students' ability to express critical evaluative thinking with precision.

One of the clearest strengths of LbE in this phase was its role in preparing students to engage in collaborative evaluation and articulate the steps of their design journey. Group presentations served as a space where students were expected not only to show their final product but also to walk through how they solved the problem, applied constraints, conducted research, and incorporated feedback. As Teacher E shared:

> "Feels really good when they're in a group and they built something, the marshmallow launcher (presentation) was like a huge success, but then they had to communicate right and I made them share a presentation and everybody has to do something and I'm feeling really good about it because like we walked through the design process, we did the problem, we did criteria and constraints. We did research."

This quote demonstrates how LbE can enhance both individual accountability and team-based communication. Because students had already practiced identifying strong and weak elements in previous LbE sessions, they entered these presentations with clearer language and expectations. The process helped them reconstruct the story of their design from start to finish, offering a cohesive narrative of what they learned and how their thinking evolved.

Challenge 1: Difficulty Expressing Evaluative Reasoning

At the same time, teachers observed that students often struggled to communicate what made one design stronger than another. While the comparative format of LbE helped students form intuitive judgments, it didn't always translate into articulate, criteria-based explanations. Teacher B noted:

> "I think most with the evaluation process. Um, and I think I hit on a lot of it is they don't know how to communicate what they're looking at that's better but getting them to put it in words is the hardest thing."

This highlights a gap between knowing and explaining. Students might correctly identify that one design meets the goal more effectively, but they lack the evaluative vocabulary to say why. Without sentence stems, targeted modeling, or reflection tools, the learning remains shallow or unexpressed. In design thinking terms, this limits their ability to provide meaningful feedback, advocate for their ideas, or justify revisions—all critical competencies in real-world problem solving.

Challenge 2: Emotional Dimensions of Peer Critique

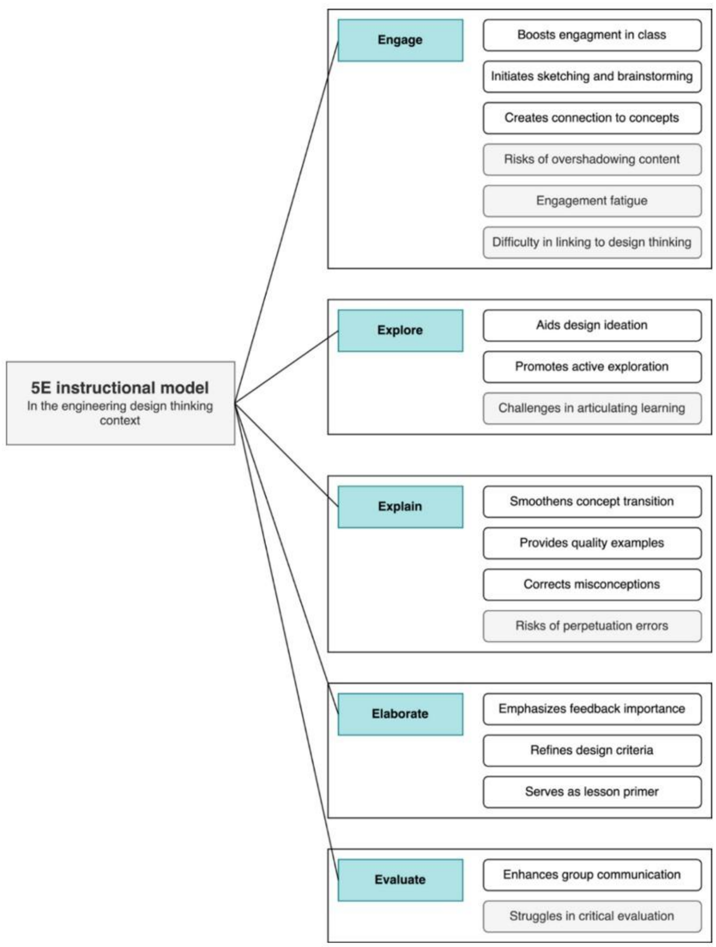
The emotional dimension of peer critique also plays a role. Without clear norms for offering and receiving feedback, some students hesitated to offer honest evaluations or struggled to interpret feedback constructively. While LbE created a structure for comparison, teachers emphasized the importance of continued guidance in teaching students how to evaluate respectfully and what to look for.

Overall, LbE in the Evaluate phase helped students transition from *"doing"* to *"explaining,"* pushing them to organize their thinking and reflect on the value of their work. But for this process to reach its full potential, especially in critical analysis, more scaffolding is needed, both in language and in evaluation strategies. With additional support, students can move beyond intuitive judgments and develop into reflective, articulate thinkers who see evaluation not as an end, but as the next step in iteration.

Organized by the phases of the 5E instructional model, findings are visually presented (Figure 3) as a concise summary of the key themes that emerged. The grey-shaded boxes in the figure highlight specific challenges and constraints encountered during the implementation of LbE within the 5E framework, offering a clear overview of both its strengths and areas for improvement.

Figure 3

Visual Summary: LbE applied in 5E framework and design thinking context



Discussion

This study examined the integration of LbE within the 5E instructional model as a means to enhance TEE. As reflected in the findings and summarized in Table 1, LbE provides a flexible, phase-specific instructional strategy that supports student learning across multiple dimensions, from activating prior knowledge to deepening evaluative reasoning. Through comparative analysis of teacher reflections and classroom observations, we found that the pedagogical synergy between LbE, the 5E model, and design thinking offers a promising approach to fostering critical reflection, conceptual rigor, and design iteration in technology-rich learning environments.

During the Engage phase, LbE functioned as a catalyst for curiosity and student motivation. By leveraging peer-generated exemplars of varying quality, teachers created opportunities for discussion, critical observation, and anticipation of key design principles. These comparative activities not only captured students' attention but also grounded abstract concepts in tangible examples, thereby enhancing relevance and participation at the outset of a unit. Students reported increased interest when evaluating past peer work, and teachers noted that this process helped activate prior knowledge in a meaningful way. As reflected in the findings and anticipated in Table 1, this engagement could wane over time if LbE tasks lacked variety or clear connections to later design phases, leading to what some teachers described as *engagement fatigue*.

During the Explore phase, LbE supported early ideation and experimentation by encouraging students to observe multiple design paths and weigh trade-offs in real time. By comparing student-generated work, learners began to move from abstract brainstorming to more grounded, criteria-based exploration. While this comparative process promoted open-ended inquiry, some students struggled to articulate what they had learned, signaling a need for more structured reflection tools to support metacognitive growth.

In the Explain phase, LbE helped students distinguish between effective and ineffective design features, which aided their understanding of underlying principles and introduced disciplinary language in context. Teachers emphasized the value of using both successful and flawed exemplars to anchor discussions about universal design, usability, and constraints. At the same time, without guided discussion, there remained a risk of students reinforcing misconceptions from the weaker examples.

The Elaborate phase emerged as a particularly fruitful context for LbE. Teachers noted that the process reinforced the importance of feedback in design cycles and gave students practice refining design criteria and constraints. Rather than launching directly into redesigns, students used LbE to revisit their previous thinking, evaluate the strength of their initial goals, and better prepare for next steps in the design process. LbE acted as a redesign accelerator, helping students pivot with purpose rather than repeat earlier missteps.

Finally, in the Evaluate phase, LbE facilitated rich group discussions and reflections on process. Students learned to connect their final product back to earlier design decisions and present their work with greater intentionality. However, the process also exposed a persistent challenge: students often struggled to verbalize what made one design better than another. While the judgment task helped sharpen intuitive thinking, teachers emphasized additional scaffolding such as sentence frames, rubrics, or peer modeling is needed to support development of evaluative discourse. From the Table 3 coding example, findings were further synthesized by mapping 5E phases to corresponding Design Thinking parallel.

This synthesis of findings as presented in Table 4 offers a more detailed overview, specifically outlining the practical application of LbE in each phase and identifying the key instructional benefits and challenges observed during its implementation.

Collectively, these findings reinforce the value of LbE as an embedded pedagogical tool. It supports not only evaluation, but also ideation, analysis, communication, and iteration. Its success, however, depends on teacher facilitation, thoughtful scaffolding, and clearly defined connections between evaluative tasks and hands-on design work. When used intentionally, LbE encourages students to move beyond surface-level engagement and develop a deeper understanding of the design process. Without these supports, though, it may lose instructional value and become disconnected from learning goals.

Rather than viewing LbE as a fixed strategy, it is more accurately understood as a responsive approach – one that adapts to student needs, instructional goals, and the iterative nature of design thinking. Its strength lies in how well it is woven into the broader flow of teaching and learning.

Table 4

Synthesis of LbE implementation findings across 5E Phases in design thinking classrooms

5E Phase	Key Function	Design Thinking Parallel	How LbE Supports	Main Benefits	Instructional Challenges
Engage	Fuels interest, taps into prior knowledge	Empathize / Discover	Boosts engagement via comparing past work and real-world context	Boosts engagement Sparks brainstorming Builds concept links	Risk obscuring content Engagement fatigue Trouble connecting to broader design thinking
Explore	Encourage inquiry, hands-on exploration	Ideate / Research	Guides ideation and sketching with examples stimulating original thinking	Aids ideation Encourages active exploration	Students struggle to articulate insights from comparisons
Explain	Clarify concepts, introduce terminology	Define / Synthesize	Solidifies conceptual understanding via comparisons; resolves misconceptions	Smooth transition to new concepts Clarifies quality Corrects misconceptions	Misconceptions may persist if not explicitly addressed in discussion
Elaborate	Apply knowledge, extend thinking	Prototype / Iterate	Promotes iterative thinking and the value of feedback; sharpens criteria and constraints	Reinforces feedback loop Refines design criteria Acts as redesign primer	None explicit, but requires intentional facilitation to maintain rigor
Evaluate	Reflect, assess, and communicate learning	Test / Reflect	Supports group reflection/synthesis Requires scaffolding in evaluative language	Enhances group communication Synthesizes full design process	Difficulty verbalizing evaluative thinking Need scaffolding for critique and feedback

Conclusion

This study explored how LbE can be integrated across the 5E instructional model to enhance TEE. When implemented intentionally, LbE helped students engage more deeply with each phase of the learning process. It supported the development of design thinking by encouraging critical reflection, iterative improvement, and peer-to-peer communication.

Across all phases of the 5E instructional model, LbE provided structured opportunities for students to compare ideas, apply feedback, and refine their understanding of design principles. It helped spark engagement in the Engage phase, guided ideation in Explore, clarified concepts in Explain, deepened reasoning in Elaborate, and encouraged reflective synthesis in Evaluate. These outcomes highlight the potential of LbE to bridge hands-on design work with critical analysis and metacognitive growth.

At the same time, the study revealed several challenges. Without scaffolding, students struggled to articulate their evaluations clearly. Repetitive formats reduced engagement over time. And without a strong instructional link, LbE sometimes felt disconnected from the broader design cycle. These limitations suggest that while LbE is a powerful tool, it must be carefully adapted to classroom context and supported through deliberate planning.

Future research should continue to investigate how LbE impacts long-term learning outcomes, especially in diverse and multilingual settings. Further work is also needed to explore how students develop evaluative language and reasoning through comparison-based activities.

Overall, LbE offers more than a method for assessing work. It creates space for students to think critically, learn from each other, and take ownership of the design process. When aligned with the goals of the 5E model and design thinking, it holds strong potential for transforming how we teach and assess TEE in the classroom.

Limitations

While this study offers valuable insight into the integration of LbE within the 5E instructional model, it is not without limitations. First, the findings are based on a small sample of high school technology educators from a single school district, which may limit the generalizability of results to other contexts or subject areas. The experiences and perspectives captured are highly contextual and may not reflect broader trends across diverse educational settings.

Second, data collection relied primarily on teacher interviews. While rich in descriptive detail, this method does not capture direct student voices or learning outcomes. Future studies should incorporate student reflections, performance data, or classroom observations to triangulate findings and strengthen claims about instructional impact.

Finally, the use of qualitative content analysis, while well-suited for exploring nuanced patterns in teacher practice, requires interpretive judgment.

Despite efforts to ensure consistency through collaborative coding and triangulation, some degree of subjectivity remains inherent in the analysis.

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Statement on Artificial Intelligence

No AI tools were used in performing or communicating the work represented in this manuscript, except for Grammarly, which was used solely for grammar and punctuation checks. All aspects of data generation, analysis, manuscript development, and revision were conducted by the authors without AI assistance.

Competing Interests

The authors have no competing interests to declare.

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