2026 ASEE
ANNUAL CONFERENCE
June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #50182

Exploring Industry 4.0 with AI-Scaffolded Research and Photovoice Reflection

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Dr. Lucas' primary goal as a professor is to engage with students in the classroom and inspire them to develop their passion, understanding, and appreciation for STEM-based research and industry roles. This is accomplished by providing well-crafted and innovative learning experiences in engineering technology courses and through extracurricular outreach. His research background is in 3D (out-of-plane) micro-electromechanical systems (MEMS) sensor and actuator design. His current teaching load primarily consists of courses related to advanced manufacturing and embedded digital systems.

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1. Introduction

The Fourth Industrial Revolution, or Industry 4.0, marks a profound convergence of cyber-physical systems, the Internet of Things (IoT), and Artificial Intelligence (AI) across the manufacturing and industrial sectors [1], [2], [3]. This transformation requires engineering graduates to possess a complex blend of highly technical digital literacy, interdisciplinary problem-solving ability, and critical soft skills (e.g., communication and collaboration) that often exceed the scope of traditional electrical engineering curricula [4], [5], [6]. This paper details a pilot study evaluating a novel, multi-modal pedagogical model designed to equip senior electrical engineering technology students with these adaptive competencies, demonstrating how the thoughtful integration of technology and active-learning methodologies can cultivate the skill sets essential for success in the modern workforce.

1.1. Problem Identification

The rapid pace of technological change driven by Industry 4.0 has created a documented skills gap between the proficiencies of current engineering graduates and the demands of modern employers [7], [8]. Crucially, this gap is two-pronged: it involves a deficit in advanced technical competencies (e.g., AI/ML operation, data analytics) alongside a critical need for cognitive and soft skills like critical thinking, digital literacy, and collaboration [9], [10]. Addressing this crisis requires an urgent and fundamental shift in engineering education, moving beyond incremental curriculum updates to a comprehensive pedagogical redesign [11].

1.2. Current Approaches

In response to the identified skills crisis, engineering education has seen an increase in efforts to incorporate modern technologies and active instructional methods. Current approaches largely fall into two categories: curricular addition and active engagement. Curricular additions include the development of new, specialized courses focused on topics like AI fundamentals [12], [13], robotics [14], [15], and cyber-physical systems [16], [17]. The second category involves adopting Active Learning strategies, such as project-based learning (PBL) and the use of virtual learning factories (VLFs) or simulated industrial environments [18], [19], [20]. Many institutions are also pursuing industry-academia collaboration to integrate real-world projects and align curriculum with industry standards, which is proving to be an effective strategy [21].

1.3. Gaps in Current Approaches

Despite the documented benefits of active learning, a significant opportunity for improvement remains. The transition to interdisciplinary Industry 4.0 content often struggles against rigid curriculum structures and the historical inertia of disciplinary silos in education [22], [23]. Furthermore, while active learning promotes engagement, open-ended research tasks can introduce a high initial cognitive load, which can lead to student frustration and reduced performance if not properly managed [24], [25]. This issue is particularly relevant when students lack prior knowledge or struggle with the organizational demands of complex projects. Finally, many technology integration efforts focus primarily on teaching the technology itself, often neglecting the simultaneous cultivation of essential soft competencies like reflective practice and non-technical communication [26], [27].

1.4. Proposed Solution

This pilot study proposes and evaluates a multi-modal pedagogical model designed specifically to meet these challenges. Our solution integrates the emerging potential of AI scaffolding with established active learning theories to create a high-impact, low-barrier entry point for exploring complex concepts. The learning experience is divided into three phases:

1. AI-Guided Outlining, which leverages large language models (LLMs) to provide organizational scaffolding and intentionally manage extraneous cognitive load.

2. Constrained Presentations (PechaKucha), which forces content distillation and enhances communication skills.

3. Photovoice Reflection, a participatory research method providing a qualitative, authentic assessment of critical self-awareness and conceptual connection to real-world applications.

This approach is hypothesized to not only enhance technical knowledge but also to cultivate the adaptable competencies essential for succeeding in the digitally transformed industrial landscape.

2. Background

The following sections details concepts that are fundamental to understanding this study. The use of AI as a scaffolding tool in education is described, and the concepts of Cognitive Theory of Multimedia Learning (CTML) and Participatory Action Research (PAR) are defined as they contribute to theoretical framework of the presented work.

2.1. AI as a Scaffolding Tool for Enhanced Learning

The integration of Artificial Intelligence (AI), specifically large language models (LLMs), into pedagogical practice is increasingly viewed through the lens of scaffolding. This is well-established as a teaching approach where support is provided to help learners master tasks they could not complete independently [28], [29]. In the context of complex technical subjects like Industry 4.0, the initial cognitive load associated with defining scope, structuring inquiry, and identifying relevant sources can be prohibitive, particularly with early-stage students [30]. By utilizing an LLM to generate a structured research outline, students are provided with a robust organizational scaffold. This mechanism reduces extraneous cognitive load, allowing students to focus their limited cognitive resources on the synthesis and critical evaluation of content rather than on the mechanics of research planning. The AI-generated outline serves not as a final product, but as a methodological roadmap, thereby promoting focused ideation and a more efficient, supported entry into unfamiliar domain knowledge.

2.2. Cognitive Theory of Multimedia Learning (CTML)

The design of the constrained presentation phase is grounded in the Cognitive Theory of Multimedia Learning (CTML), developed by Richard Mayer [31], [32]. CTML is fundamentally based on three assumptions: the Dual-Channel Assumption (separate channels for processing auditory/verbal and visual/pictorial information), the Limited Capacity Assumption (each channel can only process a finite amount of information), and the Active Processing Assumption (meaningful learning requires selecting, organizing, and integrating information). The PechaKucha [33], [34], [35] format (20 slides, 20 seconds each) is a direct application of CTML principles, specifically the Coherence Principle (excluding extraneous material) and the Modality Principle (presenting words as narration rather than on-screen text). By forcing students to distill complex Industry 4.0 concepts into concise, synthesized narratives paired with strong visual elements, this structure deliberately minimizes cognitive overload and fosters dual-channel processing. This constrained environment compels students toward deeper knowledge retention and synthesis, as they must transition from simply possessing information to effectively communicating its essential components.

2.3. Participatory Action Research

The final phase of the project, the Photovoice Reflection, draws upon the philosophical and methodological framework of Participatory Action Research (PAR) [36], [37]. PAR is a cyclical, collaborative approach that intentionally links research with action and reflection to promote social or systemic change. Its core principle is the active involvement of participants (in this case, students) as co-researchers who contribute their lived experience to the knowledge production process. Photovoice is a specific PAR technique where individuals use images and associated narratives to voice their perspectives [38], [39]. This method serves two critical functions in this study. First, it bridges the gap between abstract engineering concepts and personal experience, promoting critical self-awareness by asking students to visually interpret and narrate their connections to manufacturing advancements. Second, it captures nuanced, qualitative insights into students' conceptual understanding that are often inaccessible through traditional testing, providing an authentic and empowering assessment of their learning journey.

3. Methods

The following sections present an overview of the project, outline the protocol in place for each phase of the intervention, and share the demographics of the participants in this pilot study.

3.1. Project Overview

Based on the fundamentals described in the previous sections, this project employs a three-stage active learning model designed to strategically manage the cognitive demands of exploring complex Industry 4.0 concepts [40], [41]. First, students engage in AI-Guided Outlining [42], [43], leveraging a large language model to reduce initial cognitive load, structure their research, and promote ideation. Second, to ensure knowledge internalization, students present their findings using a PechaKucha-style constrained presentation. Finally, students perform Photovoice Reflection to connect abstract manufacturing advances to their personal, lived experiences and reinforce their conceptual understanding. The phases of this project are outlined in Table 1.

Project Phase	**Pedagogical Theory**	**Key Mechanisms**	**Anticipated Student Outcomes**
AI-Guided Outlining	Scaffolding & Sociocultural Theory	Reduces cognitive load; provides a structured starting point; promotes ideation.	Enhanced ideation; focused effort on content synthesis; efficient research workflow.
Constrained Presentations	Cognitive Theory of Multimedia Learning & Knowledge Internalization	Forces content distillation; leverages dual-channel processing; promotes concise narrative.	Improved communication skills; increased creativity; enhanced knowledge retention and synthesis.
Photovoice Reflection	Participatory Action Research	Encourages visual thinking; connects abstract	Deeper conceptual understanding; increased

	& Critical Reflection	concepts to lived experience; captures qualitative nuance.	visual literacy; critical self-awareness.

Table 1. Three-stage assignment phase structure

3.1.1.Intervention Protocol

The three phases of this integrated research assignment were designed to be completed asynchronously as homework, allowing students to manage their workload and delve into the material outside of the regular class schedule. This structure ensured that the primary course topics and scheduled laboratory activities could proceed uninterrupted during weekly class meetings. To maintain student engagement, provide necessary scaffolding, and facilitate peer learning, a dedicated in-person transitional discussion or presentation timeslot was held in class between each of the three phases (AI-Guided Outlining to Constrained Presentations, and Constrained Presentations to Photovoice Reflection). These transitional sessions served as critical checkpoints for review, feedback, and preparation for the subsequent project phase.

Project Phase	**Assignment Prompt**	**Duration (Weeks)**	**Deliverables**
AI-Guided Outlining	The initial step in your research project, you will leverage a large language model (LLM) to quickly scaffold your understanding of one of these pillars. • Choose one of the nine pillars of Industry 4. • Using your preferred AI language model (e.g., Google's Gemini, ChatGPT, Claude, etc.), generate a structured, introductory research presentation outline.	2	AI-generated outline and a description of your generation process, modifications to the prompt, lessons learned.
Constrained Presentations	Prepare a Pecha Kucha [44] style presentation on your Homework 1 Industry 4.0 topic. • Pecha Kucha, chit-chat in Japanese, is a unique presentation style.	2	Present your topic during the assigned class time in the Pecha Kucha style.

	• These presentations are known for telling stories through images rather than text and are typically brief. • They use the 20x20 rule, where each presentation consists of 20 slides, and each slide is displayed for only 20 seconds, automatically progressing to the next one. • This results in a total presentation time of 6 minutes and 40 seconds.		
Photovoice Reflection	Create a single document contains all required responses to the six photovoice reflection prompts that are assigned.	1	Completed photovoice responses.

Table 2. Classroom assignment details of the three project stages

3.1.2.Participant Information

The study participants included five students enrolled in an upper-level undergraduate course (ECET 32900 - Advanced Embedded Digital Systems) offered at a satellite campus of a large research-focused university. This campus primarily consists of students in the Midwestern United States that plan to remain in the region and join the manufacturing sector of the workforce upon graduation. The cohort consisted of four males and one female.

3.2. Data Collection

The data was collected using a metacognitive reflection assignment containing six questions. The photovoice reflection prompts (Table 3) were designed that asked students to reflect upon lessons learned by completing the semester-long project. As noted in the directions for the reflection, students will respond with an image, a caption, and a written narrative. Students submitted a single document containing their responses to the six prompts in the week following their presentation.

Directions	
Please respond to the photovoice reflection prompts using one picture (e.g., photo) and writing a narrative (e.g., voice). The narrative (minimum of 100 words for entire response) should reference the pictures and their relationship with respect to your response. Be sure to check assignment for spelling and grammar prior to submission.	
Assessment Topic	**Prompt**

AI Scaffolding	Insert an image that illustrates your view of AI as a starting point for your research. How did using this pre-generated structure, rather than starting from scratch, influence your approach to learning about Industry 4.0?
Conceptual Barriers	Choose a photo that shows how you expressed your learning of a concept from class. In your reflection, name the concept and talk about the challenges or barriers you encountered when trying to demonstrate your understanding. How did these challenges affect the way you thought about the concept and helped (or made it harder) for you to understand it?
Knowledge Application	Choose a photo that shows a concept, tool, or process in advanced manufacturing. In your reflection, explain how what you already knew or learned in class connects to its application in manufacturing. How did seeing or thinking about this connection help you understand it better?
Self-Regulation	Insert an image that represents a moment of challenge or frustration you experienced during the project. Describe the obstacle this image symbolizes. How did you navigate this challenge to arrive at a better understanding of the topic?
Career Impact	Choose a photo that symbolizes a significant advance in manufacturing and its potential impact on your career. In your reflection, explain how your chosen 'advancement in manufacturing' may impact your future professional experiences.
Collaborative Learning	Insert a photo that best represents your peer-to-peer learning experience. Explain how this peer-to-peer learning experience contributed to your overall understanding of Industry 4.0 beyond your own research.

Table 3. Six assessment topics and photovoice prompts

4. Results

4.1 Data Analysis

An inductive thematic analysis approach was used to analyze the participants' photovoice reflections. Thematic analysis is a qualitative research method used to identify, analyze, and interpret themes within a given dataset. The analysis was performed using Braun and Clarke's six-step process [45]. The authors familiarized themselves with the photovoice reflection data to generate initial themes. To streamline the process, the NVivo 14 qualitative analysis software was used to code the reflections. After identifying the themes, both authors reviewed and analyzed the data several times for consistency. Upon completion of the final round of analysis, the themes were identified. The goal of the analysis was to explore potential themes within the participants' reflections. To corroborate the findings, original quotes from the data were included to allow readers to make their own interpretations and judgments on credibility, fairness, and accuracy of the identified themes [46].

4.2 Findings

A thematic analysis of the participants' photovoice reflections identified six themes that collectively describe how learners engaged with technology during the project and how it shaped their learning experiences. The themes capture participants' perceptions of technology as a cognitive, experiential, and collaborative resource, as well as the challenges encountered throughout the project.

Theme 1: Using Technology as a Guide to Visualize Ideas

Participants described technology as a tool that helped them visualize their ideas. Digital platforms and visual aids were reported to help participants translate conceptual thoughts into tangible representations. Participants acknowledged using the predefined outline given out by AI-enabled tools as a roadmap for their project.

Example Quote: *"Overall, I believe the pre-generated structure helped me develop a cohesive presentation. Like the image, the AI-generated guide provided clear direction toward my end goal. Rather than feeling lost and trying to find my own way during the process, AI helped steer me toward my objective. It also introduced sections in the outline that I might not have considered on my own."*

Theme 2: Shifting Attitudes Toward Technology

The photovoice reflections revealed varying degrees of technology acceptance, with participants leaning toward technology use over the course of the project and into future careers. Acceptance in this case was perceived as ease of use, relevance to learning tasks, and observed value in achieving project outcomes.

Example Quote: *"For my future career, understanding and interacting with such systems will be essential, whether for process optimization, troubleshooting, or collaboration with automation technologies. This advancement highlights the growing need for technical knowledge, adaptability, and systems thinking in engineering roles. Reflecting on this reinforces that my professional experience will likely involve working alongside intelligent machines to enhance productivity and innovation in manufacturing."*

Theme 3: Promoting Experiential Learning through Tech-based Projects

The participants acknowledged that observing real-world applications of Industry 4.0 technologies helped them connect classroom concepts to practical manufacturing contexts. These experiences strengthened participants' systems-level understanding and highlighted the value of applied, experiential learning in making complex technological interactions tangible and meaningful.

Example Quote: *"In class, we learned how sensors, data analytics, and robotics communicate in real time to optimize production. I connected this to how cybersecurity protects these interactions from being compromised. Before, I saw cybersecurity mainly as an IT concern, but seeing it applied in manufacturing showed me how essential it is to maintaining smooth automation. When I thought about these connections, I understood cybersecurity as a safety layer — much like a physical guardrail — ensuring data integrity and operational safety. This realization deepened my appreciation for secure-by-design principles in Industry 4.0 systems."*

Sub-Theme 3.1: Applying Prior Experiential Knowledge

Participants explicitly connected prior experiences and existing knowledge to their use of technology during the project. Reflections indicated that past exposure to similar tools or learning contexts informed decision-making and strategy selection.

Example Quote: *"My hands-on experience with these printers came during my Co-Op at Lantech, where I worked directly with them. I designed parts, sent them to print, and managed post-processing steps such as alcohol baths and UV curing. I created components using various materials and contributed to both current production parts and prototype development. This practical exposure helped me understand the printers' capabilities and limitations. Interacting with the machines firsthand deepened my knowledge and allowed me to explain their functions more clearly and confidently when presenting the topic to the class."*

Theme 4: Cultivating Self-efficacy with Technology-enabled Problem Solving

The participants describe how technology supported their self-efficacy by helping them work through complex, unfamiliar concepts. Through tools such as simulations, research, and class discussions, they were able to visualize system behaviors, connect new ideas to prior technical knowledge, and translate theory into practical understanding. Participants used comparisons to strengthen their understanding and develop greater confidence. Participants acknowledged that persisting through confusion and achieving a better understanding of the concepts reinforced their belief that they could learn and apply advanced technical concepts effectively.

Example Quote: *"One of the biggest challenges I faced in presenting this method of additive manufacturing came from my limited background in biology and the medical field. Without a strong background in those areas, I struggled to fully grasp the idea of bioprinting, which made it difficult to convey the concept effectively. To overcome this, I approached the topic from a broader perspective, focusing on its general function. I tried to make connections between bioprinting and other 3D printing techniques I was more familiar with. Comparing it to inkjet and extrusion-based printers helped me better understand how bioprinting operates."*

Theme 5: Enhancing Critical Thinking and Systems Understanding through Collaboration

The participants describe collaboration and peer-to-peer learning as central to developing critical thinking and a systems-level understanding of Industry 4.0. Engaging in discussions, presentations, and problem-solving allowed participants to explore various perspectives and see how different technologies are interconnected. Peer-to-peer learning enabled participants to identify gaps in their understanding, connect theory to real-world applications, and view complex technical challenges through interdisciplinary lenses. This collaborative approach reinforced the value of teamwork in navigating complex, integrated industrial systems.

Example Quote: *"Collaborating with classmates allowed me to see different perspectives on Industry 4.0 applications, such as autonomous robotics, smart sensors, and data-driven manufacturing processes. Discussing challenges, sharing insights, and asking questions helped me connect theoretical knowledge from class with practical observations. This interaction broadened my understanding beyond what I could learn alone, highlighting how interdisciplinary collaboration and communication are crucial in advanced manufacturing environments."*

Theme 6: Navigating Challenges in Technology-based Projects

Participants acknowledged facing cognitive, technical, and situational challenges when working with complex technologies and project requirements. They encountered time constraints, unfamiliar data representations, complex technical language, and difficulties integrating advanced systems into real-world workflows. These factors initially led to frustration, stress, and uncertainty. However, participants reported adopting various strategies to navigate and overcome these barriers, such as prioritizing key information, organizing and cleaning data, analyzing real-world cases, observing system interactions, and managing personal well-being. Their experiences highlight how navigating complexity reinforces the importance of strategic problem-solving, reflection, and process management in technology-driven environments.

Example Quote: *"The technical language — encryption protocols, zero-trust architecture, intrusion detection — initially felt overwhelming. I struggled to connect theoretical terms to how they protect real-world manufacturing processes. To overcome this, I broke the problem down: I studied case studies of ransomware attacks on factories and how companies recovered. That process shifted my perspective from confusion to curiosity. I learned that every failure or breach provides valuable insight into system resilience. Navigating this challenge gave me a clearer, more confident understanding of cybersecurity's role in digital manufacturing."*

4.3 Discussion

This curriculum was developed with the goal of enabling students to conduct more effective introductory research into unfamiliar technical domains. The project sought to simulate information gathering and synthesis often required in professional engineering roles. The six identified themes suggest that this objective was met; participants utilized technology as a "roadmap" (Theme 1) to demystify complex concepts and build the self-efficacy (Theme 4) necessary to engage with specialized knowledge. Furthermore, the project aligned with broader program goals by fostering the "soft" professional skills such as interdisciplinary communication and collaborative problem-solving (Theme 5) that are increasingly critical in advanced manufacturing environments. By moving from technical frustration to curiosity (Theme 6), students demonstrated the adaptability and systems-level thinking that the engineering curriculum aims to instill, ultimately bridging the gap between classroom theory and the collaborative realities of their future careers.

Based on the thematic analysis findings, there were two primary ways in which the impact on learning was observed through the participants' photovoice reflections. First, the way participants communicated synthesized knowledge through the Pecha Kucha presentation format. In engineering courses, students are required to present their final projects, typically at the end of the semester, as a summative assessment. Prior studies suggest that having constraints (e.g., 20 slides, 20 seconds per slide) enables students to prioritize key ideas, reduce text-heavy slides, and adopt a more audience-centered narrative, leading to the strengthening and development of communication skills [47], [48], [49], [50], [51]. Using the Pecha Kucha presentation style, participants conveyed their proposed project ideas in a short, concise, and timed format. Second, the means by which participants gained knowledge while engaging in the project (e.g., the use of AI-enabled tools to create the project roadmap). Research competencies are skills that can help students navigate the complexities of the evolving industry demands [52], [53], [54]. With the emergence of AI in higher education, especially amid the proliferation of recent AI literacy initiatives, this study demonstrates how these technologies can be leveraged to build research competencies in undergraduate students.

5. Conclusions

5.1. Practical Summary

This pilot study introduces Industry 4.0 to senior level students by combining AI-enabled scaffolding, constrained PechaKucha presentations, and photovoice reflections. By using large language models to provide an initial organizational "roadmap," students successfully managed the high cognitive load associated with unfamiliar technical domains like cybersecurity and additive manufacturing. The subsequent presentation phase forced the distillation of complex information into concise, visual narratives, while the photovoice reflections allowed students to consider the value and impact of the experience. Thematic analysis of student feedback revealed that this multi-modal approach significantly boosted learner self-efficacy, fostered a systems-level understanding of interconnected technologies, and cultivated the collaborative communication skills essential for the modern engineering workforce. Ultimately, the work demonstrates that thoughtfully integrating AI and reflective practice can transform technology from a potential source of frustration into a tool to support career-focused learning.

5.2. Limitations and Future Directions

This pilot study had a few limitations worth noting. First, the sample size of the data collected was small, with only about five participants. While the thematic analysis of the photovoice reflections yielded rich insights, the findings are not generalizable in the broader context (e.g., across disciplines and various student populations). Future work should explore this intervention with a larger pool of students and across various Engineering Technology majors. Second, the participants were not provided with an example photovoice reflection prior to completing their reflections. In the absence of examples to guide them, participants may have struggled to understand the expectations for visual or image selection, narrative framing, and critical reflection. Future work should consider providing exemplar photovoice reflections to participants with detailed guidelines on visual selection, narrative framing, and how to critically reflect based on the learning outcomes of the instructional intervention used (e.g., Pecha Kucha and AI-enabled scaffolding). Third, technological limitations in AI-enabled tools may have introduced variations in the quality of generated responses, particularly in subscription-based services. While the instructor did not recommend a specific AI tool, it is assumed that participants used open-source tools such as ChatGPT, which are easily accessible and available to use by everyone. The quality of generated responses may have varied based on the subscription service used (e.g., free or paid). Future work should consider using a standardized or university-licensed AI-tool to ensure consistency and fairness.

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