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BOARD #125: Exploring the Role of Artificial Intelligence Tools in Enhancing Critical Thinking Skills in Engineering Prototype Design

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Abstract

The integration of AI tools in engineering education offers a unique opportunity to foster critical thinking and decision-making skills among students. As AI continues to shape industries, it is crucial for future engineers to not only understand how to use these tools but also to develop the critical thinking required to make evidence-based decisions in complex design scenarios. This qualitative study explores how AI facilitates the development of critical thinking within the context of engineering prototype design. In line of this study, our overall research questions are: (a) How do engineering students use AI tools to enhance their critical thinking skills during the engineering design process?, (b) What is the impact of AI-driven decision support on students' ability to evaluate design alternatives and constraints?, and (c) What are students' perceptions of the role of AI in supporting their decision-making process during engineering design tasks? This study includes 25 undergraduate engineering students and all participants are purposefully selected based on their experience with design tasks and their willingness to incorporate AI tools into their problem-solving processes. The selection process will ensure diversity in terms of academic performance and familiarity with AI. Following the design tasks, students are asked to maintain reflective journals, documenting their experiences, challenges, and how AI influenced their critical thinking and decision-making processes. In addition, interviews are conducted to delve deeper into their perceptions and use of AI in evaluating design alternatives and constraints. Case-study approach is employed, with students tasked to complete a series of engineering prototype design activities using AI tools such as generative design software and AI-based decision support systems. While the data collection is still in progress, the collected data from reflective journals and interviews will be analyzed using thematic analysis, focusing on themes such as critical thinking, decision-making, and AI-supported problem-solving. As potential expected outcomes, students who use AI tools might demonstrate enhanced critical thinking skills, particularly in evaluating design constraints, making evidence-based decisions, and exploring alternative design solutions. Students are likely to perceive AI as a valuable support tool for decision-making but may also identify limitations regarding over-reliance on AI. The findings will provide insights into how AI can be used effectively in engineering

education to develop critical thinking skills and offer practical recommendations for incorporating AI into engineering design curricula.

1. Introduction

Artificial intelligence (AI) is transforming engineering practice by enabling rapid design optimization and data-driven decision-making. In engineering education, AI tools offer opportunities to enhance critical thinking—a vital skill for navigating complex design challenges. For this study, key terms are defined as follows:

- **Engineering Education**: The pedagogical framework for training students in engineering disciplines, emphasizing technical knowledge and cognitive skills like critical thinking.
- **Engineering Design**: The iterative process of creating solutions to meet specified requirements, involving problem definition, ideation, prototyping, and evaluation.
- **Engineering Prototype Design**: A subset of engineering design focused on developing tangible models to test and refine concepts, requiring critical evaluation of constraints and alternatives.

Critical thinking, defined as the ability to analyze information, evaluate options, and synthesize solutions, is essential for prototype design, where students must balance competing factors like cost, feasibility, and performance. AI tools, such as generative design software and decision support systems, can augment this process by generating diverse solutions and providing analytical insights. However, their impact on critical thinking in engineering education, particularly prototype design, remains underexplored.

This study investigates how AI tools influence critical thinking during prototype design tasks, focusing on students' engagement with AI, their evaluation of design alternatives, and their perceptions of AI's role. By comparing AI-supported design to traditional methods, the study aims to provide insights into effective AI integration in engineering curricula, ensuring students develop both technical proficiency and cognitive skills.

2. Literature Review

2.1 Critical Thinking in Engineering Design

Critical thinking in engineering involves analyzing design requirements, evaluating alternatives, and synthesizing solutions under constraints. Dieter and Schmidt emphasize that engineering design requires systematic decision-making to balance trade-offs, a process rooted in critical thinking. Halpern defines critical thinking as a cognitive process involving evidence-based reasoning, crucial for assessing design feasibility and innovation. In prototype design, students must question assumptions, evaluate trade-offs, and make informed decisions, making critical thinking a core competency.

2.2 AI Tools in Engineering Design

AI tools like generative design software (e.g., Autodesk Fusion 360) and AI-driven decision support systems (e.g., MATLAB’s optimization modules) enhance design by generating multiple solutions and quantifying trade-offs. Hazelrigg’s *Systems Engineering* highlights decision-based design, where systematic methods prioritize evidence-based choices, a process AI can augment. Studies show AI improves efficiency in exploring design spaces but requires critical evaluation to address biases or impractical outputs. In industry, organizational theory research notes AI’s role in collaborative design, yet human oversight remains critical.

2.3 AI and Critical Thinking in Design Education

Recent studies explore AI’s pedagogical impact. Ruiz-Rojas et al. found that generative AI fosters collaborative critical thinking in higher education by offering diverse perspectives. Zepeda et al. report that AI-guided design activities promote ethical reasoning and critical evaluation among undergraduates. However, Walter cautions that over-reliance on AI may reduce independent analysis. In design education, Dym et al. emphasize cognitive activities like ideation and constraint evaluation, which AI can support but not replace. The *Journal of Mechanical Design* highlights AI’s potential to streamline concept selection but stresses the need for critical human judgment.

2.4 Gaps and Research Needs

While AI’s technical applications are well-documented, its impact on critical thinking in prototype design education is underexplored. Existing research focuses on general education or industry applications, with limited attention to student experiences in design tasks. This study addresses this gap by examining AI’s role in fostering critical thinking, drawing on decision-based design principles and design education literature to frame the analysis.

3. Research Questions

The study is guided by the following research questions:

1. How do engineering students engage with AI tools during the engineering prototype design process?
2. How do AI-driven decision support systems shape students' evaluation of design alternatives and constraints?
3. What are students' perceptions of AI's role in their decision-making process during engineering prototype design tasks?

4. Methodology

4.1 Research Design

This qualitative case study explores AI's influence on critical thinking in prototype design. A case-study approach allows in-depth analysis of student experiences within a real-world educational context. The study involves 25 undergraduate engineering students completing prototype design tasks over eight weeks.

4.2 Participants

Participants are purposefully selected from Singapore university's engineering program, representing mechanical, electrical, civil, and computer engineering disciplines (13 male, 12 female, aged 18–22). The inclusion of computer engineering students broadens the study's disciplinary diversity, reflecting the increasing role of AI in software-hardware integration and system design. Selection criteria include prior design task experience and willingness to use AI tools, verified through a pre-assessment survey. The survey assesses baseline critical thinking (using Halpern's critical thinking framework) and AI experience (e.g., familiarity with generative design or decision support systems), ensuring diversity in expertise.

4.3 Data Collection

4.3.1 Pre-Assessment Survey

A 20-item survey evaluates students' prior AI experience (e.g., "Have you used generative design software?") and critical thinking skills (e.g., "Rate your ability to evaluate design trade-offs"). Responses are scored on a Likert scale to establish baseline profiles.

4.3.2 Design Tasks

Students complete four prototype design tasks to accommodate the diverse disciplines, including computer engineering: (1) a lightweight bridge (civil/mechanical), (2) a mechanical component (mechanical/electrical), (3) a sustainable building facade (civil), and (4) a hardware-software integrated system, such as an IoT device controller (computer engineering). Tasks utilize Autodesk Fusion 360 for generative design and MATLAB for decision support, requiring students to define constraints, generate solutions, and evaluate alternatives. Tasks are designed to mirror decision-based design processes, emphasizing systematic evaluation, and are tailored to include system-level design for computer engineering students.

4.3.3 Reflective Journals

Students maintain journals after each task, responding to prompts tailored to their discipline. General prompts include: "How did AI tools influence your analysis of design options?" and "What challenges did you face in evaluating AI-generated solutions?" For computer engineering students, additional prompts address software-hardware integration, such as: "How did AI tools assist in optimizing system-level design constraints (e.g., processing speed vs. power consumption)?" Journals capture experiences, critical thinking processes, and AI's role across disciplines.

4.3.4 Interviews

Semi-structured interviews (45–60 minutes) explore students' perceptions and experiences. General questions include: "How did AI tools shape your evaluation of design constraints?" and "What are your views on AI's reliability in prototype design?" For computer engineering students, specific probes address system-level design, such as: "How did AI-driven decision support influence your approach to balancing hardware and software constraints?" Interviews are audio-recorded and transcribed.

4.4 Data Analysis

Data will be analyzed using thematic analysis, following Braun and Clarke's framework: (1) familiarization, (2) coding, (3) theme generation, (4) theme review, (5) theme definition, and (6) reporting. Codes focus on critical thinking (e.g., analysis, evaluation, synthesis), decision-making, and AI use. NVivo software supports coding and theme development. Critical thinking is measured by identifying instances of analysis (e.g., breaking down design constraints), evaluation (e.g., comparing alternatives), and synthesis (e.g., integrating AI insights with manual analysis) in journals and interviews. Comparisons to traditional methods are grounded in decision-based design principles.

4.5 Ethical Considerations

The study is IRB-approved, with informed consent obtained from participants. Data is anonymized, and participation is voluntary, with no impact on grades.

5. Expected Outcomes

The study anticipates that students using AI tools will demonstrate enhanced critical thinking skills compared to traditional design methods, as evidenced by improvements in three key dimensions: analysis, evaluation, and synthesis, which are central to Halpern's framework for critical thinking. These enhancements are expected to manifest across the diverse prototype design tasks, with variations by engineering discipline, and will inform pedagogical strategies for integrating AI into engineering education. However, concerns about over-reliance on AI and varied student perceptions are also anticipated, highlighting the need for balanced curriculum design.

5.1 Enhanced Critical Thinking

AI tools, such as Autodesk Fusion 360 and MATLAB, are expected to augment students' critical thinking by streamlining complex design processes and providing data-driven insights, which enable deeper engagement with prototype design tasks. Specifically:

- **Analysis**: Students are likely to show improved ability to break down design constraints into manageable components. For example, in the lightweight bridge task, AI-generated solutions may prompt students to analyze trade-offs between material strength and cost, identifying key factors more systematically than with manual methods. This aligns with decision-based design principles, which emphasize structured problem decomposition.
- **Evaluation**: AI-driven decision support systems are expected to enhance students' ability to compare and assess design alternatives. In the mechanical component task, MATLAB's optimization modules may rank designs based on performance metrics (e.g., durability vs. weight), encouraging students to critically evaluate trade-offs and justify selections using evidence. Compared to traditional methods, where students might rely on intuition or limited calculations, AI tools provide a broader and more quantifiable design space, fostering rigorous evaluation.
- **Synthesis**: Students are anticipated to demonstrate stronger synthesis skills by integrating AI-generated insights with their own reasoning. For instance, in the IoT device controller task, computer engineering students may combine AI-optimized hardware configurations with manual software adjustments to meet

power consumption goals, reflecting a higher-order integration of diverse inputs. This synthetic process is expected to be more robust than traditional approaches, which often involve sequential rather than iterative solution development.

These improvements are expected to surpass traditional methods, where students typically face time and cognitive constraints in exploring diverse solutions or quantifying trade-offs. AI's ability to generate multiple design iterations rapidly and provide analytical support aligns with Hazelrigg's emphasis on evidence-based decision-making, potentially leading to more informed and innovative prototype designs.

5.2 Disciplinary Variations

The study anticipates variations in how AI enhances critical thinking across disciplines due to the distinct nature of their design tasks. Mechanical and civil engineering students, working on tasks like the bridge and building facade, are likely to leverage AI for structural optimization, focusing on physical constraints like load-bearing capacity or sustainability metrics. Electrical engineering students, engaged in the mechanical component task, may prioritize AI's role in optimizing electrical performance (e.g., circuit efficiency). Computer engineering students, tasked with the IoT device controller, are expected to use AI to balance hardware-software constraints, such as processing speed versus power consumption, reflecting the unique system-level focus of their discipline. These differences may reveal discipline-specific patterns in critical thinking enhancement, with computer engineering students potentially showing greater reliance on AI for software-related decision-making due to their familiarity with computational tools. Understanding these variations will inform tailored pedagogical approaches for each discipline.

5.3 Student Perceptions

Students are expected to perceive AI tools as valuable for enhancing efficiency and innovation in prototype design. Positive perceptions may include appreciation for AI's ability to generate diverse solutions quickly, as in the sustainable building facade task, where students can explore multiple aesthetic and environmental options. Students may also value AI's data-driven insights, which reduce the cognitive load of manual trade-off analysis, as seen in the mechanical component task. However, negative perceptions are also anticipated, particularly regarding AI's limitations in contextual understanding. For instance, computer engineering students may note that AI struggles to account for real-world software constraints, such as compatibility with existing systems, requiring human judgment to refine solutions. Civil engineering students might highlight AI's inability to fully address site-specific factors in bridge design, such as local regulations. These mixed perceptions will provide insights into how students view AI as a supportive tool versus a potential crutch, informing strategies to foster AI literacy and critical engagement.

5.4 Implications for Curriculum Design

The anticipated outcomes are expected to underscore AI's potential to transform engineering education by enhancing critical thinking, but they also highlight the need for thoughtful curriculum design. Educators can leverage these findings to develop tasks that integrate AI tools while emphasizing critical evaluation, such as requiring students to document their rationale for accepting or rejecting AI-generated solutions. The study expects to recommend incorporating AI literacy modules to teach students about AI's capabilities, limitations, and biases, ensuring they use these tools effectively. Additionally, hybrid tasks combining AI and traditional methods can reinforce independent thinking, while reflective exercises can help students articulate AI's impact on their decision-making. These strategies will prepare students for AI-driven industries while preserving the cognitive skills essential for engineering innovation.

6. Discussion

6.1 AI's Role in Critical Thinking

AI tools are expected to enhance critical thinking by supporting systematic design processes, as outlined in decision-based design literature. Generative design software encourages exploration of diverse solutions, fostering ideation and evaluation, while decision support systems provide data-driven insights, aligning with Hazelrigg's emphasis on evidence-based decisions. Compared to traditional methods, AI enables faster iteration and broader exploration, potentially deepening critical analysis.

6.2 Addressing Over-Reliance

Concerns about over-reliance highlight the need for curricula that emphasize AI literacy and critical evaluation. Assignments requiring students to challenge AI outputs (e.g., justifying solutions with manual calculations) can mitigate this risk, ensuring AI complements rather than replaces critical thinking.

6.3 Implications for Education

Findings will guide educators in integrating AI tools to enhance critical thinking. Strategies include:

- Incorporating AI literacy training to teach students to evaluate AI outputs critically.
- Designing tasks that combine AI and manual methods to reinforce independent analysis.
- Using reflective exercises to articulate AI's impact on decision-making.

6.4 Equity and Ethical Considerations

AI integration must address equity, ensuring all students have access to tools and training. Ethical scenarios in design tasks can foster consideration of societal and environmental impacts, aligning with Zepeda et al.'s findings on AI and ethical reasoning.

7. Limitations

The study is subject to several limitations that may affect the interpretation and generalizability of its findings. First, the qualitative case-study design, while valuable for in-depth exploration of student experiences, inherently limits the ability to establish causality or generalize findings to broader populations. Qualitative methods prioritize rich, contextual insights over statistical representativeness, which may restrict the applicability of results to other educational settings or engineering disciplines. To address this, future research could incorporate mixed-methods approaches, combining qualitative insights with quantitative measures of critical thinking outcomes.

Also, the reliance on self-reported data from reflective journals and interviews introduces potential biases, such as social desirability or recall inaccuracies. Students may overstate their critical thinking abilities or AI tool usage to align with perceived expectations, or they may omit critical challenges due to lack of awareness or articulation. Triangulating data with objective measures, such as design task outputs or instructor observations, could strengthen the validity of findings in future studies.

Finally, the study's use of specific AI tools—Autodesk Fusion 360 for generative design and MATLAB for decision support—limits the applicability of findings to other AI platforms or technologies. Different tools may have varying interfaces, capabilities, or learning curves, which could influence students' critical thinking processes differently. Future research could compare multiple AI tools to assess their relative impacts on critical thinking.

These limitations highlight the need for cautious interpretation of the study's findings and underscore opportunities for future research to address these constraints through broader, more diverse, and methodologically varied approaches.

8. Conclusion

This study investigates the transformative potential of artificial intelligence (AI) tools in enhancing critical thinking skills during engineering prototype design, a critical component of engineering education. By exploring how undergraduate students from mechanical, electrical, civil, and computer engineering disciplines engage with AI tools, evaluate design alternatives, and perceive AI's role in decision-making, the research provides valuable insights into the intersection of technology and pedagogy. The expected findings—that AI tools enhance critical thinking compared to traditional methods by enabling deeper analysis, broader exploration of design spaces, and more systematic evaluation of constraints—underscore the promise of AI as a pedagogical tool. However, the anticipated concerns about over-reliance on AI highlight the need for a balanced approach that preserves human judgment, creativity, and ethical reasoning.

The study's contributions extend beyond its immediate findings, offering a framework for integrating AI into engineering curricula in ways that amplify, rather than supplant, critical cognitive skills. By grounding the analysis in decision-based design principles and design education literature, the research bridges theoretical and practical domains, providing actionable recommendations for educators. These include embedding AI literacy training to equip students with the skills to critically evaluate AI outputs, designing hybrid tasks that combine AI-driven and manual methods to foster independent analysis, and incorporating reflective practices to deepen students' awareness of AI's impact on their decision-making processes. Such strategies ensure that AI serves as a collaborative partner, enhancing students' ability to navigate complex design challenges while maintaining the intellectual rigor essential to engineering.

Moreover, the inclusion of diverse disciplines broadens the study's relevance, reflecting the interdisciplinary nature of modern engineering practice. As AI continues to shape industries—from autonomous systems to sustainable infrastructure—engineers must be prepared to leverage these tools effectively while upholding ethical and societal responsibilities. The study's emphasis on ethical scenarios and equity in AI access addresses these imperatives, aligning with emerging calls for responsible AI integration in education. By fostering critical thinking alongside technical proficiency, the findings aim to prepare future engineers for an AI-driven world where innovation and ethical decision-making are paramount.

Looking forward, this research lays the groundwork for further exploration. Longitudinal studies could assess the long-term impact of AI integration on students' critical thinking development, while cross-institutional comparisons might reveal contextual factors influencing AI's efficacy in diverse educational settings. Quantitative analyses, such as measuring improvements in design evaluation metrics, could complement the qualitative insights, providing a more comprehensive understanding of AI's pedagogical impact. Additionally, exploring AI's role in personalized learning—where tools adapt to individual student needs—could enhance engagement and critical thinking across diverse learner profiles.

Ultimately, this study serves as a call to action for engineering educators to adopt evidence-based practices for AI integration. By leveraging the insights from this research, educators can design curricula that harness AI's potential to enhance critical thinking while preserving the human elements of creativity, intuition, and ethical judgment. This balanced approach will empower the next generation of engineers to tackle increasingly complex and dynamic challenges, ensuring they are not only adept at using AI but also equipped with the cognitive and ethical frameworks to shape a sustainable and innovative future. The findings will contribute to the evolving discourse on AI in engineering education, offering a roadmap for preparing students to thrive in a technology-driven profession while upholding the core principles of engineering excellence.

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