Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #47767

Work-in-Progress - Enhancing Experimentation Skills in Engineering Students Through Reflective Memos: A Qualitative Study

Dr. Azadeh Bolhari, University of Colorado Boulder

Dr. Bolhari is a professor of environmental engineering in the Department of Civil, Environmental, and Architectural Engineering (CEAE) at the University of Colorado Boulder. She specializes in teaching the fate and transport of contaminants as well as capstone design projects. Dr. Bolhari is passionate about community-based participatory action research. Her research interests lie at the intersection of engineering and social science, focusing on understanding how innovation self-efficacy develops among engineering students with diverse neurotypes. Additionally, she investigates household resilience capacity in relation to sustainable practices, employing both quantitative and qualitative research methods.

Dr. Angela R Bielefeldt P.E., University of Colorado Boulder

Angela Bielefeldt is a professor at the University of Colorado Boulder in the Department of Civil, Environmental, and Architectural Engineering (CEAE) and Director for the Engineering Plus program. She has served as the Associate Chair for Undergraduate

Maya Leizerovich, University of Colorado Boulder

Work-in-Progress - Enhancing Experimentation Skills in Engineering Students Through Reflective Memos: A Qualitative Study

Abstract

Innovation is an important skill in engineering. Previous studies determined that experimentation skills contribute to innovation. This paper explored the role of experimentation in an open-ended team-based project, as described as part of a team-based reflective memo. The research is situated within a larger study exploring the extent to which an educational intervention in a junior-level environmental engineering course can foster innovation mindsets and confidence in students. The open-ended project asked teams of students to design a K-12 learning activity that would embed water chemistry concepts. Teams included three to five students who met with both a K-12 teacher mentor and an engineer mentor. To help foster innovation, the 10-week projects were scaffolded with a series of three team-based reflective memos and two individual reflective memos. The third memo in week 7 of the project specifically focused on experimentation, with the prompt: "For the activity you are designing, to what extent and how did experimenting assist you in searching for new ideas or creating your design?" Three undergraduate students, under the supervision of two engineering professors, conducted independent inductive coding of 7 team memos using Constant Comparison Analysis (CCA), followed by the Delphi Method to decide on final codes. Key themes included experimental design (objectives and methodology), the role of mentorship, consideration of project limitations (such as timelines), and stakeholder-centered design. A depth score analysis was performed using Moon's Map of Learning scales to assess the memos, assigning a score of 0 to 5 for each code. The highest scores related to project timelines and performing feasibility studies. There were also significant differences among the 7 teams, with overall scores ranging from 5 to 21. The findings suggest that reflective memos can reveal how experimentation played a role in the projects. The process of engaging in reflection may also help foster critical thinking and analytical skills in engineering students.

Keywords: Innovation, experimentation, reflections, critical thinking.

Introduction

Innovation is increasingly recognized as a crucial skill in engineering, driving the development of novel solutions and technologies to address complex global challenges. Previous research has identified five key domains that contribute to innovative thinking: *questioning, observing, experimenting, idea networking, and associational thinking* [1]. These domains provide a framework for understanding how individuals approach problem-solving and creativity, which are foundational skills for engineering students and professionals. However, despite their recognized importance, there is limited research that explicitly examines how educational interventions can cultivate these skills within engineering education, particularly in the context of undergraduate courses.

Several studies have emphasized the role of experimentation in fostering innovation. In particular, experimentation is central to the engineering design process, allowing individuals to test hypotheses, refine ideas, and develop practical solutions. Research on creativity in engineering suggests that students who engage in iterative experimentation are more likely to generate creative, effective solutions. For example, an experimental approach encourages students to engage in divergent thinking, an essential component of innovation that helps students explore multiple solutions to a given problem [2].

A key aspect of promoting innovation in engineering education involves scaffolding students' learning experiences. One effective method for doing so is through reflective practices. Reflective thinking has been shown to help students critically evaluate their work, recognize the impact of their decisions, and refine their problem-solving processes [3]. Reflective memos, like those used in this study, provide students with an opportunity to examine their thought processes and gain deeper insights into their approach to experimentation and innovation. The reflective process allows for the identification of key learning moments, such as how experimentation informed their design decisions and can facilitate the development of critical thinking skills that are integral to innovation in engineering.

Furthermore, mentorship plays a significant role in fostering innovation. Research highlights that mentorship, particularly when it involves both academic and professional guidance, provides students with a well-rounded perspective on their projects. Studies by de la Garza [4] and Jackson [5] suggest that mentorship in engineering courses helps students develop essential skills in both technical and non-technical domains, thereby enhancing their confidence and competence. In the context of this study, mentorship from both K-12 teachers and engineers provided students with valuable feedback and guidance throughout the design process, which likely contributed to the students' engagement with experimental approaches.

The impact of project constraints, such as time and resources, on the innovation process has also been explored in the literature. Research on project-based learning and engineering design indicates that students often face challenges in balancing creativity with practicality, especially when working within time-limited frameworks [6]. In this study, the reflective memos focused on project limitations, including timelines and feasibility, providing students with a structured opportunity to consider how constraints influenced their experimentation and design decisions.

Finally, stakeholder-centered design is another important consideration in fostering innovation within engineering education. A growing body of literature emphasizes the importance of incorporating the needs and perspectives of end-users or stakeholders in the design process [7]. By involving both K-12 teachers and students in the design of learning activities, the projects in this study encouraged students to think critically about the real-world applications of their designs and the ways in which their innovations could benefit others.

The study presented in this paper builds upon these principles by exploring the role of experimentation in a junior-level environmental engineering course, offering insights into how reflective memos can illuminate the nuanced ways in which experimentation contributes to students' innovation mindsets and their development of critical thinking skills.

Research Questions

The following research questions guide this study's exploration of the impact of an educational intervention on students' experimentation skills and how reflective writing may contribute to their growth:

- Research Question 1 - What do team-based reflective memos reveal about the role of experimentation in an open-ended class project?
- Research Question 2 - How did the intervention affect students' self-perceptions of their experimenting skills?

Methods

This research was part of a larger NSF-funded study (Award #205067) and approved by the University of Colorado Boulder's Institutional Review Board (Protocol #23-0388).

Study Setting

To help foster innovation skills among students, the project integrated an open-ended project within a Water Chemistry course required for undergraduate students majoring in Environmental Engineering. The project required teams of students to design a hands-on activity for K-12 students that would teach them a concept relevant to water chemistry. This open-ended project lasted for 10-weeks of the semester. The project was supported by required meetings with a design mentor and a K-12 teacher. The course in fall 2023 also scaffolded innovation through the use of 5 reflective memos. Three of the memos were group assignments and two were individual assignments. Each memo mapped to a different activity shown to related to innovation, aligned with five behavioral components of innovation: RM1 Questioning (group), RM2 Observing (individual), RM3 Experimenting (group), RM4 Idea Networking (individual), and RM5 Associational Thinking (group). This research paper focuses on RM3. More details on the course intervention have been previously published; see [8-9].

In fall 2023 there were 7 teams where all of the students in the group consented to participate in the research. (This included one team of three students because a student dropped the course late.) These students also completed a pre-survey to measure their innovation self-efficacy using the Very Brief Innovation Scale [10]. The majority of the students participating in the research also completed a post-survey with the same items.

Reflective Memo on Experimentation

The third reflective memo assigned in week 7 of the project asked teams to think about experimentation. The prompt was: “For the activity you are designing, to what extent and how did experimenting assist you in searching for new ideas or creating your design?” The instructions stated that the responses should be 100 to 200 words in length. Across the 7 teams, the memos ranged from 99 to 190 words (median 146 words).

The three undergraduate students began their analysis of the reflective memos by individually reviewing them, following a Constant Comparative Analysis under the supervision of two faculty. The overall process they used involved reading through the memos and noting any recurring themes, particularly those that appeared in multiple memos. These themes were then grouped into categories, which the students used to further score and analyze the writing. Scores were assigned on a 0-5 scale, where a score of 0 indicated the theme was not present in the memo, and a score of 5 indicated that the theme was well-developed and thoroughly explored.

After completing this initial individual analysis, the students used the Delphi Method to combine their categories and develop a final rubric and scoring system for the reflective memos. Despite each student taking a slightly different approach, they arrived at relatively similar categories, which simplified the process of merging them. To begin, they reviewed each other's methodology, read through the descriptions of the categories they had developed, and identified common themes. The students then created a new document to agree on which categories should remain, noting any important themes that one student had identified but others had missed.

After reaching a consensus on the general categories, the students renamed them to be both concise and clear, adding descriptions for clarity, especially for anyone unfamiliar with the analysis. The students then met with professors Bielefeldt and Bolhari to ensure that the categories were well-understood and to address any ambiguities or misinterpretations in the category titles and descriptions. The final categories included Leveraging Mentors, Project Limitation: Class Time, Conducting a Feasibility Study, Stakeholder-Centered Design: Audience, and Purpose-Oriented Experimentation (Table 1). Once the categories were finalized, the students individually scored each reflective memo using these categories, applying Moon's Map of Learning [3] to rate each out of 5. These nominally map to the levels of: 1 (noticing), 2 (making sense), 3 (making meaning), 4 (working with meaning), and 5 (transformative learning). A score of 0 was also allowed, indicating the category was absent from the memo. After the individual ratings were completed, the students reconvened to reach consensus and agree on a final score for each group's memo.

Survey

Question 3 from the Pre- and Post-ISE survey asked students to rate their confidence in using experimentation to understand how things work. Responses were on a 7-point Likert type scale.

Limitations

A small number of team reflective memos are included in the study (n=7) due to the requirement that all students on the team consent to participate in the research. Initial experimentation and overall innovation ability and self-confidence in ability varied across the students in the course. This was therefore also variable across the teams within the course. The reflective memos may not have been accurate representations of the experimentation abilities or ideas among the students. The memos were very short (less than 200 words). Because the reflective memos were graded for completion, it is uncertain whether all student teams made an honest effort to be thoughtful and submit high quality work. Some teams may have viewed the activity as busy work and therefore their memo is not an accurate reflection of their abilities. In addition, there is always some subjectivity in qualitative analysis, meaning that the assigned learning depth scores include some uncertainty. Differences between the pre/post survey responses of the students could result from more than just this single intervention and course. For example, a student might have been serving as an undergraduate research assistant during the same semester. Thus, interpretations of survey response changes cannot be conclusively attributed causally to the open-ended project intervention.

Results

RQ1. Team-based Reflective Memos: experimentation in class projects

The reflective memos were analyzed across five main categories, with results shown in Table 1. The five review categories were selected based on their relevance to fostering innovation and experimentation in the context of the student projects. Additionally, the analysis examined whether students wrote retrospectively, reflecting on completed experiments (n=2), or prospectively, planning for upcoming experiments (n=5). The group's reflections did not seem to be influenced by whether the students had already conducted their experiment, were still in the planning phase, or were planning to adjust a previously conducted experiment. There was not an obvious difference in the scores based on this factor, retrospective (10, 13) versus prospective (5 to 21, median 10). The memos with the shortest word counts received the lowest score, perhaps because it is harder to find evidence of depth of thinking and/or the level of care the teams took with the reflection.

Table 1. Summary of team scores for groups A to G on categories identified from coding their experimentation-related reflective memos.

Category	**Score on Reflective Memo 3 for Groups A-G**						
	A	**B**	**C**	**D**	**E**	**F**	**G**
Leveraging Mentors	1	0	5	0	4	4	3
Project Limitation: Class Time	3	2	4	0	0	0	0
Conducting a Feasibility Study	3	5	5	2	3	1	4
Stakeholder-centered Design - Audience	4	0	5	0	1	2	0
Purpose Oriented Experimentation	4	3	2	3	5	1	3
Total	**15**	**10**	**21**	**5**	**13**	**8**	**10**
Retrospective (R) or Prospective (P)	*P*	*P*	*P*	*P*	*R*	*P*	*R*
Word Count	*146*	*138*	*151*	*105*	*199*	*97*	*160*

Group C emerged with the highest overall scores, demonstrating strong engagement with the categories in the reflective memos. This group received a perfect score of 5/5 in three of the five categories: **Leveraging Mentors**, **Project Limitation: Class Time**, and **Conducting a Feasibility Study**. For the **Stakeholder-Centered Design: Audience** category, Group C earned a score of 4/5, while they scored the lowest in **Purpose-Oriented Experimentation** with a 2/5. This suggests that while the group excelled in considering mentorship, time constraints, and feasibility, they struggled more with articulating the purpose behind their experimental approach.

In summary, while the groups showed varied strengths across the categories, the overall analysis of the reflective memos highlighted the importance of leveraging mentorship, managing project limitations, and conducting feasibility studies in fostering innovation. Furthermore, the role of experimentation, though crucial, varied across groups, with some demonstrating stronger connections to their experimental designs than others. The findings underscore the value of structured reflection in enhancing critical thinking and innovation in engineering students.

RQ2. Self-efficacy in Experimentation

Across all of the students who consented to participate in the research, their confidence in their ability to *experiment as a way to understand how things work* averaged 4.1 (1.4 standard deviation) at the beginning of the project (n=37), compared to an average of 4.7 (1.0 standard deviation) at the end of the project (n=39). Across the population, this difference was statistically significant in a paired t-test ($p = 0.009$) and showed a medium effect size (Cohen's D 0.493).

At the beginning of the semester there were differences in the average experimentation confidence among students across different teams, ranging from a high of 5.2 on Team B to a low of 3.3 on Team A. Thus, self-confidence in this ability differed significantly among the teams. Group C (the example described in the reflective memo above) was the second least confident team initially, with an average self-confidence of 3.4 (individual scores 3 to 4). By the end of the semester the teams were much more similar in their average experimentation confidence among the individual students, ranging from a high of 4.8 on Team B and Team D (interestingly lower than the pre-survey for Team B) to a low of 4.0 on Team A. Team C was in the middle of the group at the end of the semester with an average of 4.4. Notably Team C had the largest average gain (post 1.0 higher than pre). This aligns with the qualitative analysis of the reflective memo of Team C relative to other groups.

Discussion

The results of this study emphasize the importance of structured reflection in fostering innovation and critical thinking among engineering students. The five categories used to assess the reflective memos—**Leveraging Mentors**, **Project Limitation: Class Time**, **Conducting a Feasibility Study**, **Stakeholder-Centered Design: Audience**, and **Purpose-Oriented Experimentation**—highlight key aspects of the innovation process that can be nurtured through a carefully designed intervention. Group C's performance suggests that mentorship and time management play a significant role in guiding students toward successful project outcomes. Their success in these areas indicates that the intervention likely provided valuable support for navigating the challenges of a complex, open-ended design project.

Interestingly, the analysis showed no significant difference in scores based on whether students were writing prospectively or retrospectively about their experiments. This suggests that students' ability to reflect meaningfully on their experimentation process was not necessarily tied to the stage of the experiment but rather to the depth of their engagement with the process itself. This finding is encouraging, as it indicates that students can reflect thoughtfully on their experimentation, whether it has been completed or is still in the planning phase.

The increase in post-intervention scores for experimentation confidence further supports the idea that the intervention successfully enhanced students' innovation self-efficacy, suggesting that reflective practices combined with mentorship and project-based learning can be powerful tools for fostering innovation in engineering education.

Conclusion

This study demonstrates the value of incorporating structured reflective practices into engineering education to foster innovation and critical thinking. By focusing on key aspects such as experimentation, mentorship, and project limitations, the intervention helped students develop deeper insights into their design processes and enhanced their ability to navigate complex challenges. The analysis of the reflective memos, particularly in the areas of **Leveraging Mentors**, **Feasibility Studies**, and **Purpose-Oriented Experimentation**, underscores the importance of providing students with both the tools for creative problem-solving and the support necessary to engage deeply with their work.

The lack of notable differences between retrospective and prospective reflections suggests that the timing of the experiment may not be as critical to students' ability to reflect meaningfully on their experimentation as the depth of their engagement with the process. Additionally, the improvement in students' self-reported confidence in their ability to use experimentation highlights the potential of reflective practices in promoting innovation mindsets. Overall, this study supports the effectiveness of using reflective memos as a tool to assess and enhance the innovative capacities of engineering students. Future research should explore how these findings can be scaled and adapted to different engineering disciplines, further refining the role of reflection in fostering critical thinking and problem-solving skills in future engineers.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant Number 2205067. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. Special thanks to Shane Gavney and Anvie Gowrishankar, undergraduate contributors to the reflective memo analysis, all from the University of Colorado Boulder.

References

[1] J.H. Dyer, H. B. Gregersen, and C.M. Christensen, “Entrepreneur Behaviors, Opportunity Recognition, and the Origins of Innovative Ventures,” *Strateg. Entrepreneurship J*, vol. 2, no. 4, pp.317–38, 2008.

[2] R. K. Sawyer, *Explaining Creativity: The Science of Human Innovation*, Oxford University Press, New York, NY, 2012.

[3] J. Moon, *A Handbook of Reflective and Experiential Learning: Theory and Practice*, Routledge, 2004.

[4] L. de la Garza, "The role of mentoring in engineering education," *Journal of Engineering Education*, vol. 104, no. 3, pp. 290-302, 2015.

[5] K. Jackson, "Mentorship and its role in enhancing student learning," *Engineering Education Review*, vol. 5, no. 1, pp. 40-45, 2018.

[6] S. Yoon et al., "Challenges in project-based learning in engineering," *International Journal of Engineering Education*, vol. 32, no. 2, pp. 412-422, 2016.

[7] T. Brown and J. Wyatt, "Design thinking for social innovation," *Stanford Social Innovation Review*, vol. 8, no. 1, pp. 31–35, 2010.

[8] A. Bolhari and S. Tillema, "Enhancing Engineering Students' Innovation Self-Efficacy through Design of K-12 STEM Projects," presented at the 2022 ASEE Annual Conference & Exposition, Minneapolis, MN, USA, Aug. 2022, doi: 10.18260/1-2--40763.

[9] A. Bolhari and A. R. Bielefeldt, "Board 316: Innovation Self-Efficacy: Empowering Environmental Engineering Students to Innovate," presented at the 2024 ASEE Annual Conference & Exposition, Portland, Oregon, Jun. 2024. Available: https://peer.asee.org/46895.

[10] J. M. Schar, S.K. Gilmartin, A. Harris, B. Rieken, S. Sheppard, "Innovation self-efficacy: A very brief measure for engineering students," presented in American Society for Engineering Education (ASEE) Annual Conference and Exposition. 30 pp., 2017, https://peer.asee.org/28533