WIP: Assessing the Progression of Design Process Learning in First-Year Engineering Students

Dr. Esther Tian, University of Virginia

Esther Tian is an Associate Professor of Engineering in the School of Engineering and Applied Science at the University of Virginia. She received her Ph.D. in Mechanical Engineering from the University of Virginia. Her research interests include bio-inspired robotics and engineering design education.

Jessica Taggart, University of Virginia

Jessica Taggart is an Assistant Director in the Center for Teaching Excellence at the University of Virginia, where she leads Scholarship of Teaching and Learning (SoTL) programming and supports curriculum (re)design efforts.

WIP: Assessing the Progression of Design Process Learning in First-Year Engineering Students

Abstract

This Work in Progress paper investigates how first-year undergraduate engineering students internalize and apply design process knowledge, a critical skill for success in upper-level design projects and professional practice. This study specifically explores how students' design knowledge evolves during a two-semester Engineering Foundations course sequence and evaluates the influence of prior high school engineering design experiences on their learning. The findings aim to inform curricular improvements and contribute to broader discussions on how to effectively teach design thinking at the secondary and postsecondary levels.

Introduction

Engineering design has long been a central component of ABET-accredited engineering programs, with many programs emphasizing the design process early in the undergraduate experience. First-year design courses are widely implemented, focusing on realistic projects, teamwork, and the integration of technical skills [1], [2], [3]. A spiral curriculum approach reinforces and builds upon design knowledge throughout the four-year program [4]. These curricula aim to develop attributes desired by industry employers and enhance students' design competencies. Engineering design education research has grown alongside these curricular developments, providing a scholarly foundation for effective teaching and assessment methods [5]. These efforts reflect the importance of design in engineering education and the ongoing pursuit of innovative approaches to prepare students for professional practice. Despite these efforts, the extent to which students grasp and retain design knowledge and how this knowledge progresses throughout their first year of study remains underexplored. Further investigation is needed to assess the long-term impact of early design education on student competencies and professional preparedness.

The growing integration of engineering into secondary education has created opportunities for students to develop foundational design skills before entering college. Bond-Trittipo et al. demonstrated that high school engineering programs can influence students' interests in STEM fields [6]. Similarly, Hynes et al. emphasized the importance of infusing engineering design into high school STEM courses to foster problem-solving skills and engagement [7]. Studies have also shown that early engineering experiences in secondary schools can positively influence students' performance and cognitive processes in design tasks [8]. Kado et al. observed significant correlations between K-12 prior design exposure and success in a university-level hackathon, further documenting a relationship between design self-efficacy and project outcomes [9]. However, some research has shown no significant differences in design cognition between high school students with and without pre-engineering course experience [10]. These findings underscore the potential importance of early engineering education in preparing students for success in undergraduate engineering programs. They also highlight the need for further research on the long-term impacts of pre-college engineering experiences. In particular, the extent to which such experiences influence first-year college engineering students' understanding and application of the design process have not been comprehensively studied.

At the University of Virginia, first-year engineering students with a range of prior high school experiences in engineering take a two-semester Engineering Foundations (EF) course sequence. In EF1 (Fall semester), student teams engage in project-based learning through sustainability-related design projects. In EF2 (Spring semester), students participate in client-based projects, working with real stakeholders to develop solutions to authentic engineering problems. These experiences provide students with multiple opportunities to practice their design process knowledge.

To better understand the impact of these experiences on student learning and development, this research addresses two key questions:

1. To what extent does repeated practice of the design process through project-based learning in EF enhance students' mastery of design process knowledge?
2. How, if at all, do prior engineering design experiences in high school relate to students' learning of the design process in EF?

Methods

This study employs a longitudinal approach, using a Qualtrics survey to collect design process knowledge data from three sections of first-year undergraduate engineering students enrolled in EF at three timepoints: (1) at the start of EF1 in Fall 2024, (2) at the end of EF1 in Fall 2024, and (3) at the conclusion of EF2 in Spring 2025. The study was reviewed and approved by the university's Institutional Review Board for Social and Behavioral Sciences (Protocol Number: 6881).

Participants

Participants included 93 first-year engineering students. Demographic data were not collected. All students completed the Time 1 survey, and all but one completed the Time 2 survey; data collection for Time 3 will take place at the end of the Spring 2025 semester.

Prior Engineering Design Experiences

At the beginning of the Time 1 survey, students reported their prior engineering design experiences in high school. They were asked if they had taken an engineering class during high school and, if so, to provide details about where the class was taken (i.e., at their high school or a community college, for credit or not) and its duration. Additionally, students described their experiences with the engineering design process in these classes.

Students were also asked about engineering-related experiences outside the classroom, including the duration of such experiences, the extent to which the experience involved engineering design, and their key responsibilities. This baseline data on students' pre-college design experiences facilitated comparisons between students with and without high school design education and experiences.

Design Process Knowledge Assessment

Design process knowledge was assessed using the Design Process Knowledge (DPK) assessment tool [11], which prompts students to critique a proposed design process. Students were provided with a prompt followed by a design process presented in a chart (Figure 1). The task description read:

"In a health care center, the current brake systems on wheelchairs have been identified as needing improvement, especially for patients with weak muscle strength who struggle to engage and disengage the brakes effectively. The clinic has approached you to design more user-friendly, ergonomic brake mechanisms that require minimal force, ensuring that all patients, regardless of their physical capabilities, can confidently control their wheelchairs."

Students were tasked with identifying strengths and weaknesses in the proposed design process and suggesting improvements. The description remained the same from Time 1 to Time 2 and will be used again at Time 3.

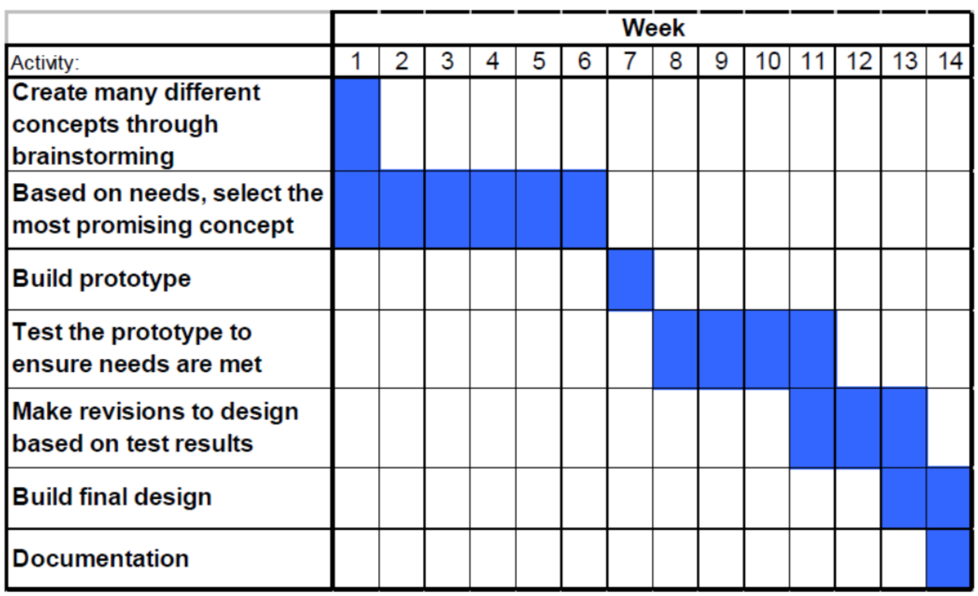

Figure 1: Proposed Design Process in Design Process Knowledge Critique [11]

Coding

Students' responses were coded by four researchers using rubrics that evaluated key elements of the design process: Problem Definition, Ideation, Evaluation and Decision Making, Building and Testing, Iteration, Time Allocation, and Documentation.

For Problem Definition, a maximum of three points were allocated for addressing client/user needs, conducting literature review and prior art search, and defining objectives and constraints (or design criteria). Students could earn up to two points for Ideation (activities such as brainstorming and generating multiple ideas) and two points for Evaluation and Decision Making (analyzing and evaluating alternative designs and making design decisions based on user needs and design criteria). For the Building and Testing, students could score up to four points for building and testing prototypes and assessing the final design against needs and criteria. Students could earn up to two points for Iteration throughout the design process and one point each for Time Allocation (for effectively managing time across design tasks) and Documentation (for recording design activities throughout the process).

Each student response was initially coded by one reader, with a second reader performing reliability coding on 20% of the responses. Weighted kappa (κw) with linear weights [12] was run to determine if there was agreement between two coders' judgement of design process knowledge (total score). At Time 1, there was a statistically significant agreement between the two coders, $\kappa w = .44$, 95% CI [.23, .65], $p < .001$. At Time 2, there was a statistically significant agreement between the two coders, $\kappa w = .52$, 95% CI [.30, .74], $p < .001$. The strength of agreement in both cases was classified as moderate according to Landis & Koch [13]. Any discrepancies were resolved through discussion.

Results and Discussion

Preliminary analyses revealed a modest but significant improvement in students' overall DPK scores from Time 1 to Time 2, though gains in individual design elements were limited. Students particularly struggled with problem definition and design evaluation and decision making, while showing stronger recognition of ideation, iteration, and time management. Prior engineering experiences had a minimal impact on DPK, with only minor differences observed based on high school coursework or out-of-class experiences. These findings highlight the need for targeted instruction in foundational design skills such as problem definition and iterative thinking.

Design Process Knowledge in the First Semester

Preliminary analyses of the first round of DPK critiques provided valuable insights into first-year students' initial understanding of the design process. Average scores at Time 1 and Time 2 can be found in Figure 2 and Table 1. We found a significant increase in students' overall DPK scores from Time 1 ($M = 4.37$, $SD = 1.62$) to Time 2 ($M = 4.79$, $SD = 1.81$), $t(91) = -2.27$, $p = .026$, Cohen's $d = 0.24$. However, no significant differences were found in individual design process element scores (Table 1).

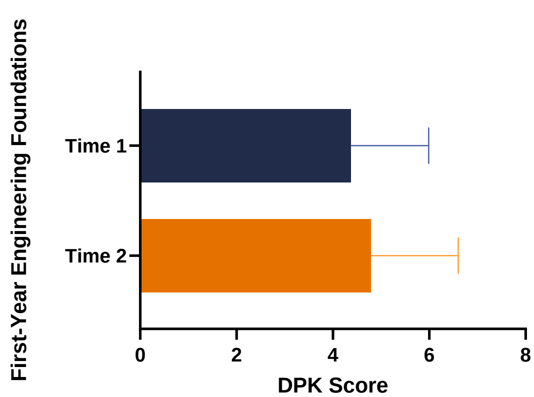

Figure 2. Average DPK scores with standard deviation measured at beginning and end of the first semester of Engineering Foundations

Table 1. Average Design Process Knowledge Scores

	Maximum Possible Points	Time 1 Mean (SD)	Time 2 Mean (SD)
Problem Definition	3	0.05 (0.37)	0.10 (0.37)
Ideation	2	0.68 (0.81)	0.79 (0.82)
Evaluation & Decision Making	2	0.14 (0.38)	0.15 (0.39)
Building & Testing	4	1.73 (0.66)	1.91 (1.00)
Iteration	2	0.68 (0.56)	0.76 (0.73)
Time allocation	1	0.81 (0.40)	0.76 (0.43)
Documentation	1	0.28 (0.45)	0.32 (0.47)
Total Score	*15*	*4.37 (1.62)*	*4.79 (1.81)*

At the beginning of the semester, we found that students failed to emphasize the importance of problem definition; just two students (2%) voiced the need to consider client and user needs, conduct literature reviews, and clearly define objectives and constraints. There was the slightest improvement by the end of the semester, with now seven students (8%) addressing problem definition. It seems that students may not yet fully grasp the foundational role of problem definition in successful design, even after completing a project involving literature searches, problem statement development, and the identification of objectives and constraints.

Similarly, students were challenged by evaluation and decision making at both the beginning and end of the semester. Only 12 students (13%) initially mentioned the importance of basing decisions on user needs and design criteria, with a negligible increase to 13 students (14%) by the semester's end. Thus, it seems that problem definition and evaluation and decision making are important target areas for instruction with first-year engineering students.

The projects students worked on during the fall semester were self-proposed sustainability-related problems on campus. They may not have fully realized the importance of addressing user needs. In the second semester of the Engineering Foundations course, students will engage in client-based projects, where they will conduct interviews with clients and users to better understand their needs. It is anticipated that this experience will enhance their ability to consider user needs throughout the design process.

Students more readily recognized the importance of ideation, iteration, and documentation at the beginning of the semester. Almost half of participants (n = 43; 46%) acknowledged the need for ideation, with nearly half of those (n = 20; 47%) also emphasizing the importance of generating *multiple* ideas. At the beginning of the semester, they knew that iteration was important (n = 59; 63%); however, most students (n = 89; 96%) failed to indicate that iteration should happen *throughout* the design process, rather than solely during prototype revisions. More students (n = 16; 17%, up from 4, or 4%) recognized this broader need for iteration by the end of the semester. Fewer students acknowledged that documentation should occur throughout the process at both Times 1 and 2 (n = 28; 30% at Time 1, n = 29; 31% at Time 2). While documentation was noted more frequently than problem definition and evaluation and decision-making, these results suggest that it remains an area for improvement.

Students also showed some skill in time allocation at the offset, with most (n = 75; 81%) offering reasonable suggestions for how to manage time throughout the design process. This trend remained consistent at Time 2, with 75% of students (n = 70) offering similar responses.

Design Process Knowledge and Prior Experience

Most participants (n = 73; 78.5%) had not taken an engineering course in high school. Those who had (n = 20; 21.5%) predominantly completed the high school coursework in their high school without college credit (n = 17; 85%, with just n = 3, or 15%, receiving college credit). For most, this experience lasted one year (n = 12; 60%) but ranged from one quarter to all four years of high school.

We explored whether there existed differences between students with prior high school engineering coursework and those without (see Figure 3 and Table 2). The only significant difference at Time 1 was regarding Evaluation and Decision making. Students without a high school engineering class experience scored higher (M = 0.18, SD = 0.42) than those with class experience (M = 0, SD = 0) based on an unequal variances independent t-test with a Bonferroni correction to α = .0071, $t(72)$ = 3.63, p < .001, Cohen's d = 0.37.

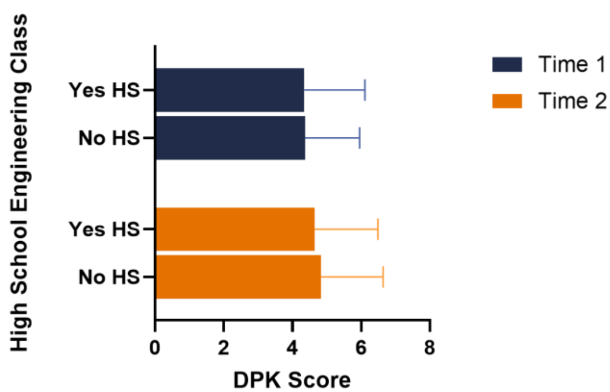

Figure 3. Average DPK scores comparing students with and without high school engineering class experience at beginning and end of the first semester of Engineering Foundations

Table 2. Average Design Process Knowledge Scores Based on High School (HS) Engineering Class Experience

	Time 1 Mean (SD)		Time 2 Mean (SD)	
	No HS (n = 73)	Yes HS (n = 20)	No HS (n = 72)	Yes HS (n = 20)
Problem Definition	0 (0)	0.25 (0.79)	0.08 (0.33)	0.15 (0.49)
Ideation	0.74 (0.83)	0.45 (0.69)	0.79 (0.80)	0.80 (0.89)
Evaluation & Decision Making	0.18 (0.42)	0 (0)	0.17 (0.41)	0.10 (0.31)
Building & Testing	1.73 (0.69)	1.75 (0.55)	1.92 (1.02)	1.90 (0.97)
Iteration	0.66 (0.53)	0.75 (0.64)	0.78 (0.70)	0.70 (0.87)
Time Allocation	0.81 (0.40)	0.80 (0.41)	0.79 (0.41)	0.65 (0.49)
Documentation	0.26 (0.44)	0.35 (0.49)	0.31 (0.46)	0.35 (0.49)
Total Score	*4.37 (1.59)*	*4.35 (1.76)*	*4.83 (1.81)*	*4.65 (1.84)*

Nearly a third of participants (*n* = 29; 31.2%) had prior engineering experience outside of the classroom, which most often included participation in high school robotics teams and shadowing engineers at professional work settings. For just over half, this experience lasted less than 3 months (*n* = 16; 55%); others had 3 to 6 months (*n* = 4; 14%), 6 to 12 months (*n* = 5; 17%), or more than 1 year (*n* = 4; 14%) of experience. When asked to what extent the engineering experience outside the classroom involved engineering design, participants indicated not at all (*n* = 1; 4%), a little (*n* = 10; 34%), a moderate amount (*n* = 10; 34%), quite a bit (*n* = 6; 21%), or a great deal (*n* = 2; 7%).

We examined whether there were differences between students with out-of-class engineering experience and those without such experience (see Figure 4 and Table 3) and found no significant differences.

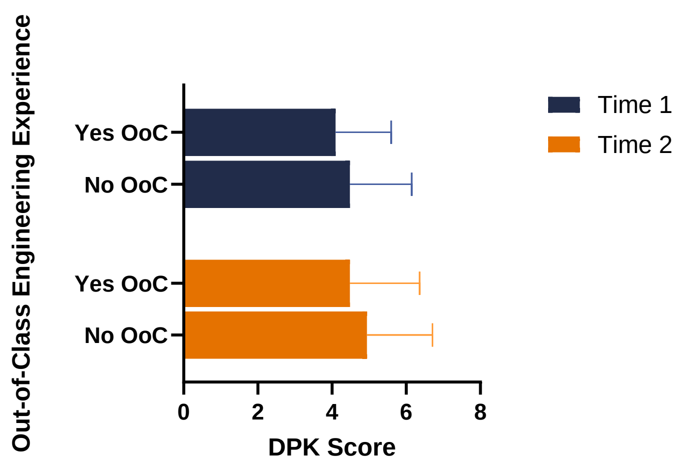

Figure 4. Average DPK scores comparing students with and without out-of-class engineering-related experience in high school

Table 3. Average Design Process Knowledge Scores Based on Out-of-Class (OoC) Experience

	Time 1 Mean (SD)		Time 2 Mean (SD)	
	No OoC (*n* = 64)	Yes OoC (*n* = 29)	No OoC (*n* = 63)	Yes OoC (*n* = 29)
Problem Definition	0.08 (0.45)	0 (0)	0.13 (0.42)	0.03 (0.19)
Ideation	0.73 (0.84)	0.55 (0.74)	0.79 (0.81)	0.79 (0.86)
Evaluation & Decision Making	0.13 (0.38)	0.17 (0.38)	0.17 (0.42)	0.10 (0.31)
Building & Testing	1.77 (0.68)	1.66 (0.61)	1.89 (0.99)	1.97 (1.05)
Iteration	0.64 (0.55)	0.76 (0.58)	0.83 (0.69)	0.62 (0.82)
Time Allocation	0.84 (0.37)	0.72 (0.46)	0.79 (0.41)	0.69 (0.47)
Documentation	0.30 (0.46)	0.24 (0.44)	0.33 (0.48)	0.28 (0.46)
Total Score	*4.48 (1.67)*	*4.10 (1.50)*	*4.94 (1.77)*	*4.48 (1.88)*

These findings suggest that while prior engineering design experiences may positively influence students' performance and cognitive processes [8], the relationship is complex and may depend on factors such as the duration and intensity of previous exposure, as well as the specific design tasks being evaluated.

Future Work

This research provides valuable preliminary insights into strengths and weaknesses in students' understanding of the design process, enabling instructors to tailor their teaching approaches. It also offers new insights into how students develop design process knowledge over time and whether prior experiences impact this learning. Additionally, this research can help secondary educators understand the long-term benefits of incorporating engineering design into high school curricula.

Further investigation is needed to better understand the factors shaping students' design learning. Future work will focus on longitudinal data collection, enabling an examination of students' design process knowledge growth over their first year of college as well as through their capstone design experience. Additionally, a deeper analysis of the qualitative aspects of prior high school engineering experiences will provide a more nuanced understanding of how early engineering education shapes cognitive and practical skills. The work will also examine the effectiveness of targeted instructional interventions aimed at fostering foundational design skills.

To extend the relevance of these findings, future studies will compare first-year engineering students' design learning across institutions with varying curricular models. This will contribute to a broader understanding of best practices in engineering education and inform the development of scalable strategies for enhancing design instruction at secondary and postsecondary levels.

By addressing these areas, this research aims to refine engineering design education, providing instructors with actionable insights to better prepare students for advanced academic and professional challenges.

Acknowledgement

The authors are grateful to Dr. Reid Bailey for generously sharing his rubrics on the DPK critique, and to Elsa Chaballa and Riley Angstadt for their assistance in coding the responses.

References

[1] C. D. Pionke, J. R. Parsons, J. E. Seat, F. E. Weber, and D. C. Yoder, "Balancing Capability, Enthusiasm and Methodology in a First-Year Design Program".

[2] T. Veltman, W. Rosehart, M. Eggermont, and D. Onen, "Evaluation and Analysis of Freshman Design Courses in Engineering," in *2011 ASEE Annual Conference & Exposition Proceedings*, Vancouver, BC: ASEE Conferences, Jun. 2011, p. 22.649.1-22.649.13. doi: 10.18260/1-2--17930.

[3] B. J. Laugelli *et al.*, “Work in Progress: A Novel Two-Semester Course Sequence that Integrates Engineering Design, Sociotechnical Skills, Career Development, and Academic Advising,” presented at the 2024 ASEE Annual Conference & Exposition, Jun. 2024.
[4] C. Venters, J. Reis, H. Griffin, and G. Dixon, “A spiral curriculum in design and project management,” in *2015 IEEE Frontiers in Education Conference (FIE)*, Oct. 2015, pp. 1–5. doi: 10.1109/FIE.2015.7344210.
[5] C. Atman, O. Eris, J. McDonnell, M. E. Cardella, and J. L. Borgford-Parnell, “Engineering Design Education,” in *Cambridge handbook of engineering education research*, Cambridge University Press, 2014, pp. 201–225.
[6] B. Bond-Trittipo, B. Berhane, and E. Lee, “Exploring the Impact of High School Engineering Exposure on Science Interests (Work in Progress),” in *2021 ASEE Virtual Annual Conference Content Access Proceedings*, Virtual Conference: ASEE Conferences, Jul. 2021, p. 37153. doi: 10.18260/1-2--37153.
[7] M. Hynes *et al.*, “Infusing Engineering Design into High School STEM Courses”.
[8] G. J. Strimel, E. Kim, S. R. Bartholomew, and D. V. Cantu, “Examining Engineering Design Cognition with Respect to Student Experience and Performance”.
[9] C. Kado, A. R. Murphy, M. Bohm, and E. Kames, “Impact of Prior Design Experiences on Undergraduate Design Success,” in *Volume 8: Engineering Education*, New Orleans, Louisiana, USA: American Society of Mechanical Engineers, Oct. 2023, p. V008T09A008. doi: 10.1115/IMECE2023-114185.
[10] J. Wells, M. Lammi, J. Gero, M. E. Grubbs, M. Paretti, and C. Williams, “Characterizing Design Cognition of High School Students: Initial Analyses Comparing those With and Without Pre-Engineering Experiences,” *J. Technol. Educ.*, vol. 27, no. 1, 2016.
[11] R. Bailey, “Don’t Tell Me What You Know, Tell Me What You Would Actually Do! Comparing Two Design Learning Assessment Approaches,” presented at the 2016 ASEE Annual Conference & Exposition, Jun. 2016.
[12] D. V. Cicchetti and T. Allison, “A New Procedure for Assessing Reliability of Scoring EEG Sleep Recordings,” *Am. J. EEG Technol.*, vol. 11, no. 3, pp. 101–110, Sep. 1971, doi: 10.1080/00029238.1971.11080840.
[13] J. R. Landis and G. G. Koch, “The measurement of observer agreement for categorical data,” *Biometrics*, vol. 33, no. 1, pp. 159–174, Mar. 1977.