

# Integrating Reflective and Technical Competencies in Engineering Design: A Cognitive Approach to Project-Based Course Redesign

#### L'Nard E.T. Tufts II, Stanford University

L'Nard Tufts is a Ph.D. candidate in Mechanical Engineering at Stanford University and a member of the Graduate School of Education's IDEAL Research Lab. Drawing on cognitive psychology and the learning sciences, his research advances integrated design education in engineering and maker-centered learning environments. He holds an M.S. in Design from Stanford, where he helped teach introductory engineering design through the Product Realization Lab, and a B.S. in Mechanical Engineering from The Ohio State University, where he founded a student-run maker club to promote hands-on, interdisciplinary learning. He previously worked at Ford Motor Company, crafting learning experiences that taught human-centered practices to non-designers in cross-functional teams and community organizations.

#### Ms. Alessandra O. Napoli, Stanford University

Alessandra Napoli is a Ph.D. candidate in Mechanical Engineering at Stanford University and a member of the IDEAL Research Lab in the Graduate School of Education. Her research focuses on supporting students through academic challenges and resilience growth, especially in project and making courses. She earned a MS in Mechanical Engineering from Stanford University and BS in Mechanical Engineering from Purdue University.

#### Shima Salehi, Stanford University

I am a Fourth year PhD student at Stanford Graduate School of Engineering. I collaborate with Engineering department here at Stanford to explore methods for improving science and engineering education.

#### Anna Lisa Boslough, Stanford University

# Integrating Reflective and Technical Competencies in Engineering Design: A Cognitive Approach to Project-Based Course Redesign

This work-in-progress case study presents a design-based research effort to enhance reflective problem-solving in an intermediate, project-based engineering design course with a hands-on CNC machining component. A core course goal is to develop intentional designers capable of making timely, informed, and well-scoped decisions in open-ended projects. Achieving the challenging balance between creative design intent and technical engineering execution can be aided by engaging in active reflection.

We analyzed three academic quarters of course delivery to identify gaps between intended and actual instructional focus, particularly around reflection. In response, we redefined learning goals and reorganized course content to integrate reflection throughout both engineering and design skill development, drawing on cognitive theories such as deliberate practice and preparation for future learning.

A key instructional innovation was the reflective brief, a structured pre-meeting activity designed to scaffold one-on-one student–instructor design check-ins. Students responded to tailored reflective prompts, documenting their key decisions and challenges for a given project phase to improve feedback readiness and the relevance of instructor guidance.

We conclude with results from our mixed-methods analysis comparing student project outcomes before and after the redesign. Preliminary findings suggest that the reflective brief and related changes enhanced project quality for students engaged more deeply in reflection. This study's instructional tools and design principles will be publicly available to support adaptation in similar project-based engineering courses.

## Introduction

The design project is ubiquitous in intermediate- to higher-level engineering courses, preparing students to tackle the types of complex, open-ended problems prevalent in the field. High achievement in these engineering design contexts requires students to exhibit both creative ingenuity and technical proficiency, an integration critical to navigating ambiguities inherent in design. Cultivating these dual competencies presents a persistent challenge for educators and students in project-based making and manufacturing courses, where measures of student performance often prioritize mastery of tools, technology, or processes over intentional design practices.

This challenge was evident in an intermediate-level, project-based engineering design course utilizing 3-axis CNC milling as its primary manufacturing process. One fundamental course objective is training designers to navigate minimally constrained projects from conception to realization—making informed, appropriate, timely, and well-scoped decisions throughout. However, this goal was previously unstated and inconsistently addressed. Traditional teaching approaches in earlier offerings presented this objective as two separate and seemingly conflicting processes, dividing design and engineering into distinct silos: design focused on creativity and novelty applied to form and meaning, while engineering centered on technical execution in

CAD/CAM tools and machine operation. This divide often resulted in an unbalanced emphasis, varying based on the instructor's or student's interests, ultimately neglecting the development of integrated engineering design problem-solving skills.

This study adopts a design-based research (DBR) [1] approach to investigate barriers to teaching and learning integrated design practice in engineering education, redesigning a target course to test for improved effectiveness. Initial course observations revealed that developing reflective practice is critical yet often overlooked in cultivating intentional engineering designers. Active reflection is essential for both technical and creative applications throughout the design process, enabling students to uncover opportunities, evaluate decisions, anticipate challenges, and adapt approaches. The study sought to embed formative opportunities for reflective practice in the course's instructional materials to effectively balance creative and technical components.

The redesign was informed by two established cognitive theories of learning, Deliberate Practice [2] and Preparation for Future Learning [3], providing a framework for restructuring the course and its embedded learning activities. Through an iterative and collaborative process over six terms, the team reevaluated learning goals, reorganized instructional content, and introduced new learning activities.

A key instructional innovation is the Reflective Brief, which aims to improve the quality of instructor-student feedback sessions. This tool directs students' attention toward their design decision-making, challenges encountered, and the support they need before engaging with the instructor. The formative reflection activity enhances student engagement with their design process and optimizes instructor feedback, making it more targeted, efficient, and actionable.

This work-in-progress paper presents the initial findings of the DBR redesign, comparing student outcomes before and after the intervention, focusing on engagement with the reflective briefs. The results highlight the potential of theory-driven course design to address instructional imbalances and promote effective engineering design education. In sharing the theoretical frameworks, course structure, and instructional materials, this work aims to provide educators with actionable tools for enhancing student reflection and improving creative and technical competencies in project-based courses.

## Background

## Target Course

The computer-aided design and manufacturing course detailed in this study is an intermediate-level technical elective for undergraduate and graduate students pursuing Mechanical Engineering or Design degrees. While a prerequisite for advanced injection molding or precision engineering courses, this course is often a terminal elective for undergraduates pursuing a design and manufacturing focus. Additionally, this course is required for any student seeking certification to operate CNC mills for personal, research, or course-related projects in the university's student-run machine shop.

The course admits 25–35 students each term and is offered three times per academic year. An overview of student enrollment data is provided in Figure 1, with students typically entering as novices to advanced beginners in design within a machining context. Over the ten-week quarter, students attend a 110-minute weekly lecture, a 4-hour structured lab during the first 3–4 weeks, and reserve open-shop hours as needed for independent project work. A weekly, 10-minute, one-on-one feedback session with the instructor replaces the structured lab from mid-quarter onward. A graduate student course assistant provides additional support through CAD/CAM checkoffs, weekly office hours, and grading input.



**Figure 1**. Target course's student demographic data during academic years 2023-2024 and 2024-2025 (n = 128). Charts show relative distributions by self-reported (a) academic level, (b) international student status, (c) racial identity, and (d) gender identity. Students' ages ranged from 20 and 60 years, with a median age of 22.

Students complete two individual design projects, each following a generalized four-phase design sequence (Figure 2), to develop CNC-machined products that meet defined requirements in response to an open-ended prompt. While prompts and processes may vary across courses and institutions, this sequence aligns with ABET defined design components [4] allowing transferability to other engineering courses with a making or manufacturing element.



**Figure 2**. Design project sequence using the Double Diamond framework, adapted from [5]. The framework (a) supported student navigation through novel design contexts by highlighting project phases and corresponding thinking modes. Expected activities were introduced as strategies during lectures or as weekly deliverables to reinforce connections between tools and tasks. Vertical lines indicate project milestones, with the middle three denoting one-on-one check-ins. While milestones support project progression, the dashed dividers illustrate the iterative, non-linear nature of design. Similarly, reflection (b) can occur at any time during the process, with explicitly prompted reflections introduced at key milestones. As defined in [4], the framework aligns with core engineering design components supporting broader applicability.

A prior version of the course was taught for over three decades by a veteran instructor who has since retired. In Autumn 2023, the current instructor began teaching the course, coinciding with the start of this research study. The primary author of this paper collaborated with the instructor as a researcher and instructional designer to refine the course's structure and content.

## Reflection in engineering design

Reflection is a critical skill for engineering designers, enabling them to analyze decisions, consider alternatives, evaluate outcomes, and adapt strategies in response to encountered or predicted challenges. Schön introduced the concept of "reflective practice" for developing practitioners across professions, emphasizing the importance of "reflection-in-action" and "reflection-on-action" in professional learning contexts [6]. He specifically highlights design professions, referring to them as ongoing, reflective conversations with and within a given situational context: "[The designer] shapes the situation, in accordance with his initial appreciation of it, the situation 'talks back', and [the designer] responds to the situation's back talk," [6, p. 79]. This iterative, responsiveness is inherent to skillful design practice, with reflection being applicable throughout the design process.

Research indicates that structured reflective activities, such as journaling or guided questioning, can significantly enhance students' ability to connect theoretical knowledge with practical applications [7]. Despite its importance, reflection is often underemphasized in traditional engineering curricula, which focus on technical skills, process execution, and artifact quality in instruction and evaluation. However, through cultivating reflective practices, students can develop a greater awareness of their decision-making process and better recognize why, when, and how to apply their skills in future contexts.

We utilized four empirically-validated reflective practices from Salehi's problem-solving framework [8] to aid students in making informed and intentional decisions. These were paired with expert-like questions for problem-solving, sampled and adapted from Price et al. [9], to model behavior and engage students with these practices (Table 1).

<b>Reflective Practice</b>	Expert-like Questions			
Reflection on Problem	How am I framing the problem?			
Definition and Assumptions	Are my assumptions/simplifications appropriate?			
Deflection on Knowledge	What do I know that can help me solve the problem?			
Reflection on Knowledge	Is there any additional knowledge that I need?			
Deflection on Streets are	What are different methods to solve the problem?			
Reflection on Strategy	How well is my current approach working?			
Deflection on Colotion	How good is my solution?			
Kenection on Solution	Should I integrate or further iterate?			

Table 1	. Sample	expert-like	questions	for ref	lective	practice
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## **Cognitive Theories of Learning**

Cognitive theories such as Deliberate Practice [2] and Preparation for Future Learning [3] provide valuable frameworks for structuring effective educational experiences. Deliberate Practice (DP), a seminal theory on developing expertise, suggests mastery is achieved through effortful, deliberate practice of a given skill. DP requires four key elements: 1) a set of distinct subgoals that together form the desired skill, 2) intentional learning activities for each subgoal tailored to the learner's incoming level of preparation, 3) provision of detailed, specific, and timely feedback on the learner's performance in these activities, and 4) opportunities for the learner to incorporate this feedback to improve their performance. Previous work [10] has adapted these elements for introductory engineering design courses, integrating them through redesigned learning activities and teaching tools. A similar approach was tailored to and implemented for intermediate-level courses in this study, as detailed in the methods section.

Preparation for Future Learning (PFL) theory guided the creation of additional feedback and feedback incorporation opportunities, further enriching the course structure. PFL posits that learner-centered activities completed before instructor-driven content dissemination are opportunities for building and organizing new knowledge. Additionally, these activities better prepare students for future instruction by improving content relevance and applicability [3]. PFL was applied to low-stakes assignments and quizzes that assessed comprehension of previously covered material and engaged students in the productive struggle of confronting novel problems, which the instructor provided optimized methods to solve in subsequent lectures. Such PFL activities and quiz questions turned lectures into additional opportunities for students to receive feedback on their understanding.

## Methods

This study uses a design-based research (DBR) approach to iteratively improve its target course. Well-suited for educational contexts, DBR combines theory-driven inquiry with practical interventions to address real-world teaching and learning challenges. This methodology integrates observation, iterative redesign, and evaluation to refine instructional practices and align them with desired learning outcomes [1].

The DBR process for this study unfolded over two academic years (AY) and included four primary phases: (1) teaching observation to establish a baseline of current practices, (2) redefining learning goals to align with student-centered outcomes, (3) curriculum redesign to address gaps and enhance learning experiences, and (4) implementation and iteration to test, refine, and improve the redesigned course. Each phase involved close collaboration between the lead researcher and course instructor, ensuring interventions were grounded in both cognitive theory and practical teaching considerations. A fifth, yet-to-be-completed, analysis phase will occur following implementation to further validate student outcomes, systematize methods, and explore additional applications. A timeline of this process is illustrated in Figure 3.

AY2023-2024			AY2024-2025					
	1		2	3	4 5			5
Teac	hing Observ	vation	Redefine Learning Goals	Redesign Curriculum	Im	plementati	on	Analysis
A23	W24	S24	SU	24	A24	W25	S25	SU25
A = Autumn W = Winter S = Spring SU = Summer AY = Academic Year								

Figure 3. Timeline of the design-based research process across two academic years.

By integrating continuous evaluation and feedback into the redesign process, this approach sought to develop a refined curriculum that fosters reflective design practice, intentional decision-making, and technical competency for CNC milling. The following sections detail the methods employed during each phase of the DBR process, highlighting the strategies used to achieve the study's objectives.

# Teaching Observation (Autumn, Winter, and Spring, AY 2023–2024)

Throughout the initial academic year under the newly hired instructor, researchers conducted teaching observations of lectures, labs, and one-on-ones to document student engagement, identify learning barriers, and provide an external perspective on course delivery. This approach allowed investigators to uncover expert blind spots in teaching methods and gain an unbiased understanding of student experiences. Observations revealed discrepancies between instructional intent and actual delivery, establishing a baseline for evaluating current practices and identifying areas for improvement. Additionally, pre- and post-course student surveys were implemented and refined each term. These surveys captured useful data on student backgrounds, perspectives, and performance, offering further insights to inform the redesign process and evaluate its efficacy.

# Redefining Learning Goals (Summer 2024)

All course content, including the 1,590 lecture slides presented in AY 2023–2024, was thoroughly evaluated to synthesize salient learning goals. Over three decades of instruction had resulted in the accumulation of content driven by variations in staff interests, resource allocations, and technology access. This necessitated reevaluating and restructuring student-centered outcomes to align more closely with the course's primary objectives.

Using the elements of deliberate practice as a grounding framework, the research team worked extensively with the course instructor to clarify and reorganize the learning goals to focus on: 1) Refining individual design approaches, informed through reflective practice, 2) Supporting appropriate decision-making for computer-aided manufacturing, and 3) Ensuring safe and efficient operation of Haas 3-axis CNC mills. Goals were chosen to support students' development of intentionality in their engineering design practice. This process involved mapping course concepts, revising the syllabus, and aligning the learning goals with desired outcomes. Subgoals were created to provide a foundation for curriculum redesign.

## **Redesigning Curriculum (Summer 2024)**

The curriculum redesign built on the clarified subgoals, focusing on improving knowledge organization, enhancing transferability, and embedding reflective practices across creative and technical applications. Outdated or irrelevant material was removed to streamline the curriculum, aligning it more closely with the redefined learning goals, reducing cognitive load, and ensuring that all content served a clear instructional purpose. Activities were developed to foster reflective design practices that students could transfer to varied contexts, incorporating deliberate practice exercises and creative PFL tasks grounded in real-world design scenarios to build both confidence and competence. Additionally, lectures, labs, and projects were explicitly mapped to the subgoals, creating structured opportunities for deliberate and effortful practice. This alignment ensured that students consistently engaged with core skills in a way that reinforced their learning trajectory and prepared them for the challenges of open-ended design tasks.

Guided by DP, the redesigned curriculum prioritized feedback as a critical component of learning. New formative assessments were introduced to provide detailed, specific, and timely feedback. To ensure consistency and clarity, the instructional team was supported with training materials, rubrics, and feedback guides. The sequencing of projects was adjusted to allow multiple opportunities for students to apply feedback, refine their skills, and demonstrate measurable growth.

## Implementation and Iteration (Autumn, Winter, and Spring AY 2024–2025)

The redesigned curriculum was implemented across the second academic year, focusing on practice, feedback, and reflection. This iterative approach provided opportunities for continuous refinement based on observed outcomes, student feedback, and instructor insights. Each quarter facilitated the evaluation of new methods, improvements to instructional materials, and the resolution of unforeseen challenges.

To analyze the impact of the redesign, mixed methods were employed. These included the preand post-quarter engineering perceptions survey, project and final grades, and a scenario-based design activity used as a pre-, mid-, and post-quarter assessment. This activity served a dual purpose: (1) Performance Evaluation: It measured student progress in developing their individual design and decision-making approaches, assessing the effectiveness of course interventions and (2) PFL Teaching Tool: It served as a PFL exercise to familiarize students with relevant design decisions they are likely to encounter in their final projects and to reinforce reflective practices This approach ensured that students received meaningful learning experiences while providing actionable data to inform course improvements.

## The Reflective Brief

A central component of the redesigned curriculum is the Reflective Brief, a structured learning activity that supports creative and technical competency through reflective practice. The existing course structure included 10-minute instructor-student feedback sessions on deliverables at key project milestones, e.g., concept sketches, prototypes, or CAD models. During the teaching observation phase of the DBR process, these meetings varied widely in effectiveness due to two primary issues.

First, there were unclear expectations for the structure and purpose of these sessions. Some students treated them as casual check-ins, while others viewed them as formal progress reports, leading to anxiety and uncertainty about whether discussions should be student- or instructor-led. Many students expected step-by-step guidance, influenced by prior experiences in introductory courses where well-meaning shop assistants would readily solve any problem, requiring students to merely execute instructions rather than develop self-sufficiency.

Second, student preparedness was inconsistent. Effective meetings occurred when students had a clear understanding of their completed work, a vision for their next steps, and targeted questions. However, many students arrived with the required deliverables but lacked a deeper understanding of their process or the rationale behind their decisions. Instead, these sessions often centered on narrow technical problems or overcoming decision paralysis with little to no emphasis on honing design approaches or developing adaptive problem-solving skills. This lack of focus limited opportunities for effective feedback and meaningful learning outcomes related to design practice and informed decision-making.

To address these challenges, the Reflective Brief was introduced as a structured tool to prepare students for these one-on-one sessions. Modeled after engineering design memos, it provides a clear framework for students to organize their thoughts and reflect on their design process before meeting with the instructor. Suggested reflective prompts tailored to each design stage require students to document their key design decisions, significant challenges, and the top three areas for guidance or feedback.

This structured approach serves multiple purposes. By requiring students to think through their process and its outcomes prior to receiving feedback, the Reflective Brief encourages a deeper awareness and better articulation of their individual practice of design. It provides a model for communicating their process with their instructor and an expectation for the relevant questions to ask oneself throughout a design process. It improves preparedness, ensuring students arrive at their one-on-one session with specific, targeted questions that make discussions more focused and productive. Additionally, by simulating an industry-relevant practice, the Reflective Brief bridges academic learning with professional expectations, reinforcing the importance of clear communication and independent problem-solving. While this paper focuses on the impact of pre-meeting reflection, future studies will examine the effects of incorporating post-meeting reflection on how to integrate feedback into next steps.

Preliminary findings indicate that the Reflective Brief significantly enhanced the effectiveness of one-on-one meetings. Instructors reported more meaningful and productive interactions, while students expressed increased confidence in articulating their challenges and applying feedback to advance their projects.

## Analysis

This section describes the methods and processes used to evaluate the data collected through the redesigned course interventions. The primary aim was to assess the integration and impact of reflective practice within a technical engineering curriculum. The analysis of three terms focused on student responses to reflective briefs, the effectiveness of the automated analysis agent, and the generation of reflection scores to evaluate the quality of student reflections.

## Data Collection and Organization

Each student was required to complete a Reflective Brief assignment prior to their one-on-one feedback session with the instructor. The Reflective Briefs consisted of three question categories—Summary, Techniques, and Concerns—with specific guiding questions for each category. Students submitted their responses via the university's learning management system (LMS), and submissions were graded for completion.

Responses were collected at three key phases of the engineering design project—Concept Generation, Selection & Refinement, and Functional Prototyping—with guiding questions tailored to each phase. These respective briefs are included in Appendices A–C. Note that during Autumn 2024, a Reflective Brief for Functional Prototyping was omitted due to scheduling constraints and workload adjustments resulting from Election Day and Thanksgiving Break.

While most submissions were text-based, some students submitted handwritten responses in image or PDF formats. For this analysis, only text-based responses were included. Handwritten responses were converted into typed text using text conversion tools to ensure consistency.

Collected data was organized into comma-separated values (CSV) files, categorized by project phase. Each phase was further divided into three separate files based on the question category. This method allowed for focused analysis of each question independently, thereby reducing complexity and improving the accuracy of the analysis.

## Automated Analysis of Reflective Brief Data

## Leveraging Automated Analysis Agent

We utilized an automated analysis agent, powered by large language models (LLMs), to process the segmented data. Multiple agents were tested through the institution's AI portal to ensure data protection, and validated against human coded analyses. Among the models evaluated, Anthropic's Claude (version 3.5-sonnet) was found to be most effective for analyzing our text-based responses. The AI model was instructed to identify general themes, common omissions, unique realizations, and evidence of reflective practice across all student responses (Appendix D). The agent returned comprehensive feedback, including actionable recommendations for the instructor (Appendix E), significantly reducing instructor workload while delivering valuable insights into student performance.

To mitigate potential AI errors and hallucinations, we found that limiting data input to a single question at a time yielded the most reliable results. Each question was analyzed in separate sessions to maintain the agent's focus and accuracy. Consistent prompts were crafted to guide the AI's analysis and ensure interpretive consistency.

#### Generating Reflection Scores

The Reflection Score (rscore) was a key component of the automated analysis. Using OpenAI's ChatGPT (version 40) via the institution's AI portal, each student's responses to the summary and technique question categories were evaluated based on four reflective practices as defined by [8]: Problem Definition and Assumptions, Knowledge, Strategy, and Solution (Appendix F). Each practice was scored from 0 to 5 points, resulting in a cumulative score of up to 20 points per question and 40 points per Reflective Brief. Rscores were normalized based on the number of Reflective Briefs assigned each term.

ChatGPT-40 processed responses, generated scores, and compiled results into a CSV file. While Anthropic's model performed well with textual analysis, we found that OpenAI's was better for computing numerical scores and exporting results in the desired format. Human scorers verified the AI-generated scores and justifications for alignment and accuracy. This detailed scoring allowed for quantitative assessment and comparison across cohorts.

## Data Integration and Visualization

After scoring and thematic analysis, the data was combined and tidied using R 4.4.2 [11]. This involved merging student responses, scores, and AI feedback into a single structured dataset. There were no instances of data needing to be removed due to incompleteness as every enrolled student submitted at least one reflective brief. Final project grades were also included to assess the impact of reflection on student outcomes. Human verification ensured that records remained accurate and corresponded correctly across different phases and student identifiers.

## Quantitative Post-Survey Analysis

The pre- and post-survey given to students during the Winter and Spring terms of AY 2023-2024 and the Autumn term of AY 2024-2025 were combined by student identifier using R 4.4.3 [11]. Two datasets were maintained: one included pre- and post-survey data from students who completed both, and the other included only completed post-surveys, as the expert-like decision-making section related to their final project was exclusive to the post-survey. Incomplete responses were retained if the individual question being analyzed was complete.

For this initial analysis, only the expert-like decision-making subsection was examined. In total 49 students across the three quarters completed the post-survey (with one student responding

twice; only their first response was retained). As questions were modified and refined across quarters, only consistent expert-like reflection questions posed to all students are reflected in this preliminary analysis.

## **Results and Discussion**

## Student Perceived Engagement in Reflection

To assess perceived engagement in reflection practices, we analyzed a post-survey question related to the expert reflection questions students considered during their final project. The survey asked: "The following is a list of questions that can arise during the design and manufacturing process. Select any questions that you had to answer for yourself in order to move your project work forward this quarter. Some may not apply." The answer options and the percentage of students who selected each option are shown in Table 2.

**Table 2.** Expert-like reflection questions [9] included in post-surveys across offerings, showing the number of students reporting engagement with the question during their design process.

	Number of students who reported engaging with the question (%						
	Are my assumptions/ simplifications appropriate?	Is there any additional knowledge that I need?	How well is my approach working?	How good is my solution?			
Students in offering without Reflective Brief (W24) (n=15)	10 (67%)	9 (60%)	12 (80%)	13 (87%)			
Students in offerings with Reflective Brief (S24 + A25) (n=34)	23 (68%)	24 (71%)	28 (82%)	32 (94%)			

Fisher's exact test was used to check for significant differences between the quarter without the Reflective Brief (Winter AY 2023-2024) and the combined quarters with the Reflective Brief (Spring AY 2023-204 and Autumn AY 2024-2025). No significant results were found (alpha = .05).

# Student Actual Engagement in Reflection

The analysis of reflective performance scores across different project phases reveals a noticeable decline in students' reflective capabilities when describing specific design techniques, particularly during the transition from concept generation to concept selection and refinement, as illustrated in Figure 4. Specifically, students exhibit lower proficiency in applying and reflecting on specific techniques and strategies during the concept refinement phase. This trend aligns with

qualitative analysis, where Claude 3.5-sonnet noted frequent omissions of "systematic evaluation methods" in student responses. This was highlighted as a primary area for improvement, with structured decision-making tools being a top recommendation for enhancing performance during this phase.



**Figure 4**. Mean student reflective performance with standard error across design phases from final project reflective briefs (Spring 2024).

In the subsequent phase of functional prototyping, the data exhibits a shift in reflective practice. Specifically, there is an increase in scores related to technique specificity, which becomes more prominent than process summarization. This shift is clearest when students reflect on their Problem Definition & Assumptions and Solution (Figure 5) and suggests that as students progress from conceptualization to concrete prototyping, alternative prompts become more effective in facilitating engagement with their processes.



**Figure 5**. Mean student reflective performance with standard error across design phases, segmented by reflective practice, from final project reflective briefs (Spring 2024).

To assess the impact of reflection on student performance, we computed a generalized linear model with a quasibinomial family and logit link function which revealed a significant relationship between normalized cumulative reflective scores and final project grades across the Spring and Autumn 2024 terms. The logistic model was used to account for the natural ceiling of 100% for the final project grades as opposed to a linear model, and only considered the normalized cumulative reflection score as a dependent variable. The criteria for significance was alpha = .05. The model produces a coefficient for normalized cumulative rscore of 0.09480 (Standard Error: 0.02058, t value: 4.607, Pr(>|t|): 3.24e-05), which is highly significant (p < 0.001). This indicates that higher cumulative reflective scores are strongly associated with better final project grades. The plot in Figure 6 visually supports this finding, with the fitted logistic regression curve (blue line) demonstrating an upward trend, signifying that as the normalized cumulative reflective scores increase, so do the final project grades. That said, there is a ceiling

effect in final project scores with many students gaining a perfect grade, and hence our current analysis may underestimate the correlation between reflection score and the quality of student performance.



**Figure 6**. Logistic regression of normalized cumulative reflection scores vs final project grades across Spring and Autumn 2024 terms

Students who consistently engage in structured reflective exercises demonstrate higher performance on their final projects. This finding has important pedagogical implications, suggesting that incorporating reflective practices into design curricula could enhance student achievement in the engineering field. A comparison of the mean cumulative reflective scores and final project grades between the two academic terms further supports this conclusion. The data indicates that students in the Autumn 2024 cohort scored higher on average in both cumulative rscores (Figure 7) and final project grades (Figure 8) compared to their Spring 2024 counterparts. Notably, the mean final project grades for the Autumn 2024 cohort were higher and exhibited a tighter clustering around the mean, indicating less variability in performance. This suggests a more uniform level of achievement within this cohort, pointing to improvements in instructional methods or other supporting factors.



**Figure 7**. Scatter plot of mean cumulative reflection scores with standard error (normalized by reflection opportunities) plotted across Spring and Autumn 2024 terms.



**Figure 8**. Scatter plot of mean final project grades with standard error (scaled to 100) plotted across Spring and Autumn 2024 terms.

It is evident from this comparison that the structured reflective exercises have contributed to higher and more consistent grades in the Autumn 2024 cohort. However, further analysis is needed to disentangle the specific factors contributing to these findings, whether they stem from

cohort differences, instructional improvements, or external influences. These insights underscore the critical role of reflective practices in fostering student success and advocate for their continued and expanded use in educational curricula within the engineering design context.

#### Conclusions

This study redesigned an intermediate-level project-based engineering design course to integrate formative opportunities for developing reflective practice through its instructional materials, aiming to balance the creative and technical skill sets required in engineering design. The iterative DBR process spanned over two years and will continue at least through Summer 2025. Introducing the Reflective Brief at critical design stages improved instructor-student communication, enhanced the effectiveness of feedback sessions, and yielded better measures of student reflection. Initial results indicate a positive correlation between reflective scores and final project grades, supporting the integration of reflective practices to boost student performance.

Variations in student performance across reflective practices and project phases suggest that the nature of reflective practice evolves with project progression and levels of preparedness. Higher scores for Techniques Utilized as compared to Process Summary questions during functional prototyping imply students are better equipped to reflect on specific techniques when working with tangible outcomes, whereas challenges during concept refinement highlight the need for better instructional strategies for systematic evaluation and idea selection. These insights underscore the necessity for tailored instructional approaches at each stage of the design process.

## **Limitations and Future Work**

One limitation of the current work is the potential inconsistency and optimism in grading student projects. Most final project grades fall between 80-100%, providing a limited range for thorough analysis. Future studies could benefit from evaluating student work based on clearly defined, objective criteria aligned with the restructured course learning goals, allowing for more accurate assessments and meaningful data.

Future work should also control for differences in student populations within and between each term. For the offering without Reflective Briefs, the post-survey is given immediately after their most reflective assignment: a photo essay of their final design project. This timing could bring reflective questions to the forefront of students' minds, making it harder to discern at which point they initially engaged with expert-like questions. For offerings with Reflective Briefs, students may struggle to recall all the questions they asked themselves throughout the process. Future analyses will compare these results to the rscores generated from Reflective Briefs during the quarter, providing more insight into post-survey accuracy in measuring recall of reflective practices.

To better measure students' actual engagement in reflection, the Reflective Briefs can be implemented regularly as an ongoing Process Journal. This approach, currently being piloted, involves weekly submissions for students to track their progress and reflect on their practices, providing more opportunities for deliberate practice of reflection and targeted instructor feedback. By integrating reflection into students' weekly routines, these journals would help students maintain a continuous dialogue about their design processes, challenges, and achievements and allow instructors to monitor development and identify areas needing support.

Furthermore, including multi-modal data in the Process Journal, such as text, images, and diagrams, provides a richer dataset to understand how reflective practices evolve over time and across project phases. To fully leverage this complex data, further exploration and validation of AI tools are needed to support the instructor's feedback role. These AI tools could facilitate the analysis of diverse data types and help instructors provide timely and precise feedback, thereby enhancing instructional efficacy.

# Acknowledgments

We utilized resources from Stanford University's "AI Playground" to explore and validate our approaches to incorporating AI tools into the feedback generation process. Through this portal, Anthropic's Claude.ai, version 3.5-Sonnet, helped automate the analysis of student reflective responses by identifying general themes, common omissions, unique realizations, and evidence of reflective practice. OpenAI's ChatGPT, version 40, helped generate reflection scores for student responses, providing a quantitative measure of reflective practice. We thank the developers of these tools which are available using the links below. https://aiplayground-prod.stanford.edu https://claude.ai

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## Appendix A

## Reflective Brief: Concept Generation Phase

#### Instructions

Before our scheduled 1-1 meeting, take some time to reflect on your process and document your design journey thus far. We'd like you to take note of what approaches are working and share any questions, concerns, or challenges you may have encountered. This will help us tailor and focus our discussion to ensure our time together is productive. Additionally, this brief is designed to help you capture valuable insights into your design process that you can include in your final project photo essay! If you so choose, feel free to screenshot or print your responses to use as a conversation guide during your 1-1 this week.

Consider **some or all** of the items below. You don't need to write a lot, bullet points are fine. Keep it concise!!! The idea here is to get you thinking, not to write an essay.

## **Summary: Concept Generation**

Summarize your concept generation process. Some questions for you to consider:

- How I you interpret and make sense of the provided project prompt?
  - From what sources did I seek inspiration?
  - How many ideas did I generate?
  - What dominant themes governed my ideas?
  - How many distinct themes did I consider?
  - What makes my concepts unique or original?

# **Techniques: Lateral Thinking**

Describe the specific techniques you used to think laterally during your ideation process. Some questions for you to consider:

- What strategies did I use to ensure I fully explored possible project directions?
- In what ways did I challenge my assumptions, change my environment, and/or shift my perspectives to uncover nonobvious solutions throughout my process?
- What did I do when I got stuck or reached a dead end?
- How wide vs. how deep did my thinking go?

# **Concerns: Top Three Pain Points**

Make a numbered list of your top three concerns that you'd like specific help or feedback on during your 1-1. Some things for you to consider:

- Where I'm stuck
- Strategy questions
- Process concerns
- Concept clarification

## Appendix **B**

#### Reflective Brief: Concept Refinement Phase

#### Instructions

Before our scheduled 1-1 meeting, take some time to reflect on your process and document your design journey thus far. We'd like you to take note of what approaches are working and share any questions, concerns, or challenges you may have encountered. This will help us tailor and focus our discussion to ensure our time together is productive. Additionally, this brief is designed to help you capture valuable insights into your design process that you can include in your final project photo essay! If you so choose, feel free to screenshot or print your responses to use as a conversation guide during your 1-1 this week.

Consider **some or all** of the items below. You don't need to write a lot, bullet points are fine. Keep it concise!!! The idea here is to get you thinking, not to write an essay.

## **Summary: Concept Refinement**

Reflect on how you refined your ideas and selected your top three project concepts. Here are some guiding questions you might consider:

- How have I incorporated feedback from instructors, peers, or other sources since my initial sketches?
- What was one key insight or moment that helped me narrow down my ideas?
- What adjustments did I make to my designs or process, and what inspired these changes?
- What synthesizing or evaluation strategies did I use to reduce my many ideas to my top three?
- In what ways do each of my top three concepts address different needs, incorporate different approaches, or emphasize different values?
- What specific experiences, skills, or values influenced my top three choices, and how do they reflect my growth as a designer?

## **Techniques: Selection and Scoping**

Describe the specific techniques or strategies you used to narrow down and define the scope of your final project. Here are some guiding questions you might consider:

- What did I find to be the most significant constraint, and how did it influence my decision-making?
- How did I adapt any overly ambitious ideas to ensure they fit within my available resources (e.g., time, materials, budget)?
- How did I bolster the weaknesses of my early ideas or build on their unique strengths to maximize their design potential?
- What trade-offs did I make in choosing these concepts, and how did I prioritize certain features over others?
- How do I plan to break down my big idea into specific tasks with deadlines, and what strategies will I use to stay on track?
- How does my proposal facilitate opportunities for prototyping, testing, feedback, and iteration?

• What potential setbacks could impact my project's success, and how can I prepare to address them proactively?

## **Concerns: Top Three Pain Points**

List your top three concerns you'd like specific help or feedback on during your 1-1. Here are some common issues you might consider:

- Where I'm stuck
- Strategy recommendations
- Process concerns
- Requirement clarification

# Appendix C

## Reflective Brief: Functional Prototyping Phase

#### Instructions

Before our scheduled 1-1 meeting, take some time to reflect on your process and document your design journey thus far. We'd like you to take note of what approaches are working and share any questions, concerns, or challenges you may have encountered. This will help us tailor and focus our discussion to ensure our time together is productive. Additionally, this brief is designed to help you capture valuable insights into your design process that you can include in your final project photo essay! If you so choose, feel free to screenshot or print your responses to use as a conversation guide during your 1-1 this week.

Consider **some or all** of the items below. You don't need to write a lot, bullet points are fine. Keep it concise!!! The idea here is to get you thinking, not to write an essay.

## **Summary: Prototyping Process**

Summarize your prototyping process. Some questions for you to consider:

- What were my project's most critical functions, fits, or interactions?
- What driver questions did I aim to address with my prototype?
- What did I learn about my process, design, or assembly approach through prototyping?
- What criteria did I use to test and determine the success or failure of my prototype?
- If successful, are there opportunities to further optimize or improve my design? If unsuccessful, how will I iterate based on the insights I gained?

## **Techniques: Decision Making**

Describe the specific techniques you used to make evaluative decisions during your prototyping process. Some questions for you to consider:

- To what extent did I break down my project into specific, testable sub-components (such as parts, features, joints/fits, processes, or other granular sublevels)? Why did I choose this level?
- How did I prioritize the most important aspects to figure out through this functional prototype?
- Were my driver questions well-scoped? How effective was my testing plan?
- How many prototypes did I decide to make? How many questions were answered? In what ways did I (or might I) maximize learning by testing multiple considerations at once?

# **Concerns: Top Three Pain Points**

Make a numbered list of your top three concerns that you'd like specific help or feedback on during your 1-1. Some things for you to consider:

- Where I'm stuck
- Strategy questions
- Process concerns
- Concept clarification

## Appendix D

Sample Input Prompt for Autumn 24 Concept Refinement Evaluation (Claude 3.5-sonnet)

Attached is the isolated response data for Question 1 as comma-separated values. Using these 26 student responses, analyze the data to identify and provide insights into the following five key areas related to reflective practices in their concept-refinement and selection processes: General Themes:

- Identify and list recurring reflective themes found across the responses.

- Provide specific examples of these themes and explain their relevance to effective concept refinement and selection.

Common Omissions:

- Highlight critical reflective elements that are frequently absent or underdeveloped in student responses.

- Explain why these omissions are significant and how they impact the quality of the concept-refinement and selection process.

Unique Realizations:

- Identify particularly novel or insightful realizations described by students.

- Provide examples and explain why these realizations are meaningful or demonstrate advanced reflective thinking.

Evidence of Reflective Practice:

- Categorize the reflective practices evident in the responses using the following framework:
- -- Reflection on Problem Definition & Assumptions
- -- Reflection on Knowledge
- -- Reflection on Strategy
- -- Reflection on Solution

- For each category, provide examples from the responses that illustrate student engagement in these reflective practices.

Recommended Areas for Student Improvement:

- Based on the data, outline 2-3 actionable recommendations for improving students' reflective practices.

- Tie these recommendations to specific examples or trends observed in the responses.

For each of the five areas, include specific examples or insights drawn from student responses to support your analysis. Provide concise explanations for why these findings are significant in the context of improving reflective practices in concept refinement and selection.

Included response data in comma-separated values as plain text

## Appendix E

Sample Generated Output for Autumn 24 Concept Refinement Evaluation (Claude 3.5-sonnet)

Based on the student responses provided, here's an analysis of the five key areas related to reflective practices in their concept-refinement and selection processes:

1. General Themes:

Recurring reflective themes found across the responses include:

a) Personal interest and passion: Many students emphasized selecting concepts they were excited about or personally interested in.

Example: "What would be most meaningful for me? What would I be most excited to work on?" b) Feasibility and scope: Students often considered whether their ideas were achievable within the given timeframe and with available resources.

Example: "focused on doable/feasible ideas in time alloted (or ideas I thought would be reasonably difficult, but not too difficult to make)"

c) Functionality vs. aesthetics: Many responses showed students grappling with balancing form and function in their designs.

Example: "I am greatly interested, as many others are, in the connection between form and function, aesthetic and mechanics."

d) Manufacturability: Students frequently mentioned considering how their designs could be manufactured using CNC machines.

Example: "I try to incorporate features that are unique to CNC that can't be accomplished with a manual mill."

These themes are relevant to effective concept refinement and selection because they demonstrate students considering multiple factors in their decision-making process, balancing practical constraints with creative aspirations.

# 2. Common Omissions:

Critical reflective elements frequently absent or underdeveloped in student responses include: a) Detailed analysis of feedback: While some students mentioned receiving feedback, few provided in-depth reflections on how they incorporated specific suggestions.

b) Systematic evaluation methods: Many students relied on intuition rather than structured decision-making tools for concept selection.

c) Reflection on personal biases: Few students explicitly acknowledged how their personal preferences might influence their design choices.

These omissions are significant because they impact the quality of the concept-refinement and selection process. A more systematic approach to evaluating feedback and concepts could lead to more informed decisions, while recognizing personal biases could help students make more objective choices.

3. Unique Realizations:

Some novel or insightful realizations described by students include:

a) Redefining traditional objects: "In a way, I think two of my top three choices are redefining something that is traditional. We've been interacting with soap and light switches in the same way for as long as they have been invented and there haven't been any radical and better changes to them."

b) Importance of abstraction: "From there, I began to abstract the concept of a whistle, exploring its most basic elements. I think this ultimately led to a more creative process, with many more unique ideas rather than a collection of small household items that make a whistling sound when you blow into them"

These realizations demonstrate advanced reflective thinking by showing students' ability to challenge existing paradigms and explore new approaches to design.

4. Evidence of Reflective Practice:

Categorizing the reflective practices evident in the responses:

a) Reflection on Problem Definition & Assumptions:

Example: "I finally realized it when [my instructor] told me it's more of an engineering problem rather than a design problem"

b) Reflection on Knowledge:

Example: "I asked CAs about how they might go about machining different aspects of different designs, and I learned about internal and external threading tools on the cnc"

c) Reflection on Strategy:

Example: "To downselect to my top three ideas, I used a pugh down selection strategy loosely defined by the project requirements."

d) Reflection on Solution:

Example: "I made some adjustments on the bike body to make it more machinable on the CNC. I made a version with attachable handle bars and pedals, and one with all of the bike parts as one body."

5. Recommended Areas for Student Improvement:

Based on the data, here are 3 actionable recommendations for improving students' reflective practices:

a) Implement structured decision-making tools: Encourage students to use formal methods like decision matrices or weighted criteria to evaluate their concepts more systematically.

b) Deepen feedback analysis: Guide students to reflect more critically on the feedback they receive, explaining how specific suggestions influenced their design choices.

c) Explore personal biases: Prompt students to consider how their personal preferences or experiences might be influencing their design decisions, and encourage them to seek diverse perspectives.

These recommendations address the observed trends of relying on intuition for decision-making, limited incorporation of feedback, and lack of acknowledgment of personal biases in the design process.

## Appendix F

Sample Input Prompt for Autumn 24 Concept Refinement Evaluation (ChatGPT-40)

Perform a complete analysis of all 26 student responses to evaluate evidence of reflective practice using the provided response data in comma-separated format. Students responded to reflective prompts provided during the concept refinement and selection phase of a design project as an assignment for an intermediate-level collegiate engineering design course. In the background, take your time and critically assess the quality, depth, and specificity of reflection in the following four categories as evidenced in each student's response: Reflection on Problem Definition and Assumptions, Reflection on Knowledge, Reflection on Strategy, and Reflection on Solution. Beyond a simple description of what they did, assess evidence of a metacognitive analysis of their design process and engagement with the prompting questions. Assign a numerical score from 0-5 for each category and calculate a summary score reflecting the overall quality of the response. Include a concise justification for the summary score, providing a concise yet clear rationale and citing a specific quote from the response that substantiates how well it meets the criteria for reflective practice or where it falls short.

Output your complete analysis data in CSV format. Create a new file that uses the following column headers for each student response:

sis\_id: The sis\_id corresponding to the student response

rscore\_definition: The score for reflection on problem definition and assumptions.

rscore\_knowledge: The score for reflection on knowledge.

rscore strategy: The score for reflection on strategy.

rscore solution: The score for reflection on solutions.

rscore: The total summary score calculated as the sum of the four reflection scores.

justification: A brief explanation for the scores assigned, referencing specific elements of the student's response.

Response Data:

Included response data in comma-separated values as plain text